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ROCKY MOUNTAIN PENEPLAINS NORTHEAST OF YELLOWSTONE PARK

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ABSTRACT

The Beartooth Mountains are truncated by two remarkably flattish surfaces. The summit plateau has an altitude of 12,000 or more feet over a large area in the most rugged portion of the range. The subsummit plateau extends the length of the range on both sides of the medial divide, at an elevation of about 9,500–11,000 feet. These plateaus are interpreted as remnants of two former peneplains. The summit peneplain can hardly be older than Oligocene, whereas the subsummit peneplain appears to be of Pliocene age.

FOREWORD

The Beartooth Mountains are the front range of the Rocky Mountains northeast of Yellowstone Park. They extend from Livingston, Montana, on the northwest to Clark Fork of Yellowstone River, in northwestern Wyoming, on the southeast. The range rises abruptly 3,500–4,000 feet from the Great Plains and the Bighorn Basin to a sky line that is in many places remarkably even and continuous (Fig. 1). It is separated by the upper Clark Fork on the southwest from the Absaroka Range, which is closely related to it.

The Beartooth Range is a huge anticline with a core of pre-Cambrian granitoids and schists flanked by Paleozoic and Mesozoic sedimentary formations. It is generally overturned and overthrust toward the Great Plains, from which it is sharply separated by the

profound Beartooth fault of post-Middle Eocene age. The lower southwest slope beyond Clark Fork is buried beneath the huge pile of Upper Miocene volcanics which form the adjoining Absaroka Range.[1]

FIG. 1.—East front of the Beartooth Range near the Montana-Wyoming boundary. Note the abrupt rise from the Bighorn Basin to the even crest of the subsummit plateau. The Beartooth fault is at the base of the range. The elevation varies from less than 6,000 feet at the base of the range to 10,000 feet at its crest.

THE SUMMIT PLATEAU

The most extensive and typical remnant of the summit plateau is along the main axial divide north of the Wyoming boundary (Fig. 2). Its noteworthy features are numerous tabular peaks and broad, flattish ridges, over an area of several square miles at altitudes of 12,000–12,400 feet, in the most rugged portion of the range.[2] Numer-

[1] A more detailed account of the stratigraphy and structure is given by the writer in "Summary of the Geology of the Beartooth Mountains, Montana," *Jour. Geol.*, Vol. XXXI (1923), pp. 441–65.

Reference should be made also to the Livingston, Montana, and Absaroka, Wyoming, folios, *U.S. Geol. Survey, Geol. Atlas, Folios 1 and 52.*

[2] Typical views are shown in *Jour. Geol.*, Vol. XXXI (1923), pp. 447–48.

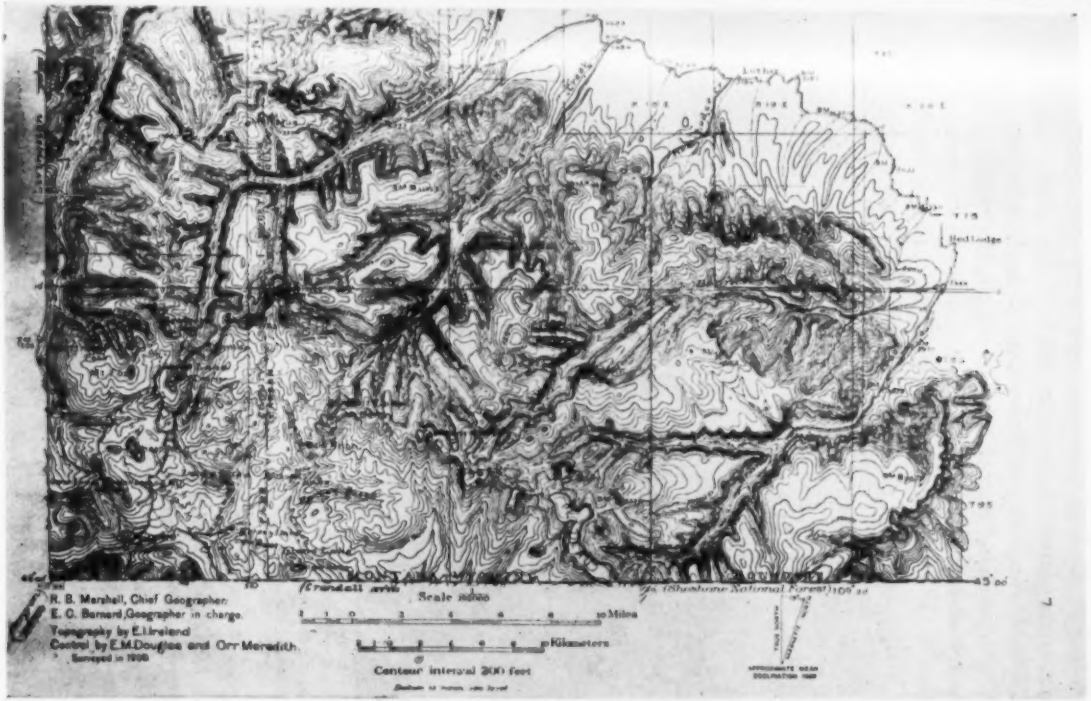
R. B. Marshall, Chief Geographer.
E. G. Barnard, Geographer in charge.
Topography by E. Ireland
Control by E. M. Douglas and Orr Meredith
Surveyed in 1908
Scale 62500
10 Miles
10 Kilometers
Contour interval 200 feet

FIG. 2.—Topographic map of the central part of the Beartooth Range. Note the summit plateau remnants between 109° 30′ and 109° 40′ along the axial divide, extensive areas of the subsummit plateau on both sides of this divide, and the narrowness of the canyons which trench it. Granite Peak is just east of the intersection of 45° 10′ and 109° 50′.

ous vigorous streams and former glaciers have cut deeply into the margins of the plateau, but in spite of this severe erosion its low relief has been remarkably well preserved. A few isolated peaks farther northwest along the main divide indicate the former great extent of this surface. Granite Peak, which rises to an altitude of 12,850 feet in the central part of the range—and thus is the highest point in Montana—is a short, flattish ridge (Fig. 3), whose crest is

FIG. 3.—Granite Peak, the highest mountain in Montana, whose even crest is a remnant of the summit peneplain. Its elevation is 12,850 feet. Looking southwest from West Rosebud Plateau.

about 800 feet above the nearest part of the summit plateau, 6 miles to the southeast. Sawtooth Mountain, 5 miles farther west on the same divide, is a similar ridge at an altitude of slightly less than 12,000 feet. Mount Wood, 8 miles north of Granite Peak, probably reaches this summit level with an elevation of about 12,700 feet, but having been reduced to a sharp peak by the encroachment of several cirques, the former surface is not preserved.

Thus remnants of the summit plateau exist for about 20 miles along the axis of the range and for about 8 miles at right angles to it,

at altitudes ranging from approximately 12,000 to 12,850 feet. Accordance of summits is a common feature of individual ranges of the Rocky Mountains, but the noteworthy characteristic of the Beartooth summit surface is its flattishness at thousands of feet above base level over many square miles of deformed rocks of diverse constitution.[1]

FIG. 4.—A remnant of the subsummit peneplain northwest of Granite Peak. The elevation at the crest is about 11,400 feet and at the bottom of the canyon is about 9,000 feet. The base of Granite Peak is in the left foreground.

THE SUBSUMMIT PLATEAU

Much of the Beartooth Range consists of a subsummit plateau, which is in general 1,500–2,000 feet below the summit plateau. The evenness of the plainsward margin of this subsummit plateau, except where indented by deep valleys or cirques, is impressive (Fig. 1). This rim has an altitude of about 9,500–11,000 feet, and is generally about 3,500 to more than 4,500 feet above the plains.

[1] For a brief description and sketches of a similar case in Central Asia, see W. M. Davis, "A Flat-topped Range in the Tian Shan," *Appalachia*, Vol. X (1904), pp. 277–84.

This plateau extends almost the entire length of the range on the eastern and northeastern side of the axial divide. It consists of very broad, gently undulating ridge crests 2,500–4,000 or more feet above the main streams (Figs. 2 and 4). Some of these flattish crests are 3–4 miles wide, and some are about 10 miles long. The largest flats have an area of 10–20 square miles. As described in another article:

> The dissection is least advanced in the southern half of the range and has progressed farthest in the northwestern portion, but even here the old surface is partially preserved in flattish tracts of considerable size. East Boulder and West Boulder plateaus, which are shown on the topographic map of the Livingston, Montana, quadrangle, are fairly typical remnants, but the best examples are in the south-central part of the range, just north of the Wyoming boundary.

Silver Run and Line Creek plateaus, southeast of Red Lodge, are conspicuous remnants in this area (Figs. 5 and 6). Even in that rugged portion of the range northwest of Granite Peak known as the Granite Range, where numerous canyons are cut deeply into the plateau, the intervening ridge crests are remarkably flat (Figs. 2 and 4).

Thus a noteworthy characteristic of the subsummit plateau on the plainsward side of the range is its flattishness upon diverse pre-Cambrian rocks throughout an area that is about 70 miles long and 10 or more miles wide. An equally striking feature is the slight dissection of some of the larger remnants in spite of their occurrence at high altitudes between deep canyons with vigorous streams. The refilling of a dozen main narrow valleys and their short tributaries would restore in large measure this subsummit surface to its former gently undulatory shape.

The subsummit plateau on the southwestern slope of the range has been considerably modified by an ice-cap.[1] Instead of the typical grassy flats or broad *felsenmeers* on the northeastern side of the axial divide, the plateau here is characterized by rounded hills and ridges of bare rock interspersed with valleys and rock basins which contain scores of small lakes. Lake Plateau is typical of this area.[2] This glaciated plateau has a general elevation of about 10,000 feet north of

[1] For a description of this area see a forthcoming article by the writer, "Glaciation of the Beartooth Mountains."

[2] See the Livingston, Montana, topographic sheet of the U.S. Geol. Survey.

FIG. 5.—The subsummit peneplain southwest of Red Lodge. Part of Silver Run Plateau with Line Creek Plateau beyond Rock Creek. The elevation is about 10,000 feet. Looking southeast toward the plains.

FIG. 6.—Silver Run Plateau just east of the axial divide. Remnants of the summit plateau form monadnocks in the background. The massive peak has an elevation of 12,350 feet.

the Wyoming boundary, but it rises to 11,000 feet in places along the base of the axial divide, where it is about 1,500 feet below the summit plateau. In northern Wyoming this surface slopes rapidly toward Clark Fork.[1]

The higher portions of this glaciated area can be traced around the southern end of the summit plateau into the unglaciated subsummit plateau on the eastern side of the main divide. In the northwestern half of the range the divide between the subsummit and glaciated plateaus is hardly a mile wide. Northwest of Mount Douglas, west of Sawtooth Mountain, and southeast of Granite Peak the subsummit plateaus on opposite slopes are obviously parts of a formerly continuous surface (Fig. 2).[2] It is evident from these relations that the subsummit plateau formerly covered the greater part of the range.

ARE THESE PLATEAUS REMNANTS OF PENEPLAINS?

Although flattish surfaces which truncate folded rocks are generally interpreted as peneplains, it is advisable to inquire briefly if the plateaus of the Beartooth Mountains may have some other origin. In addition to planation by running water, several causes of the accordance of summits in alpine mountains have been advocated,[3] but none of them seems applicable, except possibly in slight degree, to the Beartooth Mountains. These alternative explanations have been advanced chiefly to account for subequality in altitude of sharp peaks and narrow ridges "in an alpine range where there are no remnant plateaus directly referable to a common, uplifted and dissected peneplain."

It should be noted clearly that the Beartooth Mountains contain remnants of two broad plateaus which are separated by a considerable vertical interval. The slight difference in elevation of numerous tabular peaks and flattish ridges along the axial divide in-

[1] U.S. Geol. Survey, Crandall, Wyoming, topographic sheet.

[2] See also the Livingston, Montana, topographic sheet.

[3] N. S. Shaler, "Spacing of Rivers with Reference to the Hypothesis of Base-Leveling," *Bull. Geol. Soc. Amer.*, Vol. X (1899), pp. 263–76.

R. A. Daly, "The Accordance of Summit Levels among Alpine Mountains: The Fact and Its Significance," *Jour. Geol.*, Vol. XIII (1905), pp. 105–25; "Development of Accordance of Summit in Alpine Mountains," *Geol. Survey Can., Mem. 38* (1912), pp. 631–41.

dicates a formerly extensive, continuous summit surface without pronounced local relief. As this surface was developed upon folded rocks of diverse character it must have been an erosional plain. Similar features of the subsummit plateau in a much better degree of development and preservation force the same conclusion in regard to its origin.

The geographic relations of the range and the date of the orogeny debar marine erosion as a possible factor in the formation of these plains. It is also extremely improbable that the summit plateau represents the exhumed marine plain upon which the basal Cambrian sediments were deposited. Certain features weigh strongly against such an origin: (1) the extent of the remnants of the summit plain in the most vulnerable positions in the range; (2) the lack of sedimentary outliers; (3) the improbability that denudation of the axial portion of the folded range would stop at the contact of the sedimentary formations and the underlying beveled crystalline rocks. It is obvious that neither interpretation applies to the subsummit plateau. Although the accordance of alpine summits has been ascribed in part to alpine glaciation.[1] and erosion by ice-sheets has been advocated as a possible cause of planation,[2] it seems certain that the rôle of glaciers in the Beartooth Mountains has been mainly that of increasing the relief.

Inasmuch as these plateaus could not have resulted from marine planation or glaciation, they must have been formed mainly by the action of wind or running water. Wind erosion appears to be capable of reducing extensive areas to surfaces of low relief.[3] It is, perhaps, a more potent agent of planation under optimum conditions than is commonly realized. It is doubtful, however, that conditions have been adequately favorable to permit the leveling of the Beartooth Range by eolian erosion. Undoubtedly eolation has been at times an important factor in the modification of the topography and the

[1] R. A. Daly, *ibid.*

[2] F. E. Wright, "Ice-Cap Beveling," in "Some Effects of Glacial Action in Iceland," *Bull. Geol. Soc. Amer.*, Vol. XXI (1910), p. 723.

[3] S. Passarge, "Die Inselberglandschaften in tropischen Afrika," *Naturwiss. Wochenscher.*, Vol. III (1904), pp. 657–65.

W. M. Davis, "Geographic Cycle in an Arid Climate," *Jour. Geol.*, Vol. XIII (1905), pp. 381–407. "Leveling without Baseleveling," *Science*, N.S., Vol. XXI (1905), pp. 825–28.

transfer of materials, but it is considered to have been in this region a co-operative process of subsidiary importance rather than the dominant process of denudation. On the other hand, numerous examples of the extensive or almost complete planation of great masses by running water are exhibited in present topographies as well as in stratigraphic relations within the geologic column. Moreover, the existence of the central mountainous tract along the axis of the range, irrespective of the resistance of the rocks, as an unreduced erosion remnant upon the subsummit plateau, is substantial evidence of the origin of the latter through peneplanation. Hence it is concluded that both plateaus are remnants of old-age surfaces which were essentially peneplains.[1]

The view might be entertained that these plateaus are portions of a formerly continuous surface which has been deformed through faulting or warping. A fault boundary for the summit plateau, except locally, is precluded by the spurs that extend to the northeast beyond the inner margin of the subsummit plateau (Fig. 2). The precipitous descent in many places of more than 1,000 feet is due to glaciation at lower levels, and not to faulting. That the lower surface could not be a downwarped portion of the upper one is demonstrated by this interdigitate relationship as well as by the normal erosional slope which connects both plateaus on the northeast side of the axial divide (Figs. 2 and 6).

Thus the characteristics and relations of the summit and subsummit plateaus in the Beartooth Mountains warrant the acceptance with reasonable certainty of two epochs of extensive peneplanation in the Cenozoic history of the range.

AGE OF THE PENEPLAINS

The age of these peneplains cannot be precisely determined at this time, but their development, uplift, and dissection must have occurred within certain fairly well-defined limits. In any attempt to solve this outstanding problem, several factors and lines of evidence need to be considered and evaluated carefully according to all of their interrelations. Let us first attack the problem by considering the summit peneplain.

[1] It is evident that the present surfaces are not the original plains, for they have been modified by many erosive processes.

Summit peneplain.—In a previous article it was stated:

> The peneplanation of the deformed mass most probably was not accomplished before the Oligocene, and perhaps not until the Miocene. Several lines of evidence . . . . point to the conclusion that the peneplain is not older than the Miocene, and may possibly be of Pliocene age.[1]

Since that article was published the writer has reached the conclusion that the summit peneplain can hardly be older than Oligocene or younger than early Miocene.[2] The bases of this determination follow.

Although the time required for the reduction of a region to approximate base level cannot be estimated with sufficient accuracy to permit its use in dating topographic features except in the most general manner, it is probable that the huge resistant mass of the range was not truncated until long after the major adjustments of the Beartooth overthrust had been made. This profound fault is essentially contemporaneous with the Heart Mountain overthrust, beyond the southeastern extremity of the Beartooth Range, which is post-Middle Eocene.[3] Hence the assumption seems warranted, without unduly pressing the facts in the case, that the Beartooth summit peneplain was not completed prior to the Oligocene.

A record of events concurrent with the planation should exist in the environs of the Beartooth Mountains, unless obliterated by subsequent changes. Hence the Absaroka Range and the Great Plains should be sources of critical data.

It is unlikely that the Beartooth mass could have been planed down into the pre-Cambrian without the development of a similar surface on the much weaker rocks of the adjacent Absaroka Range. Two old erosion surfaces are available there for comparison: one at the base of the Upper Miocene "early basic breccia"; the other on the crests of a few summit ridges.

Deep dissection of the precipitous east front of the Absaroka

[1] "Summary of the Geology of the Beartooth Mountains, Montana," *Jour. Geol.*, Vol. XXXI (1923), p. 463.

[2] The modification results fro n critical reconsideration of all the available data; especially, the former provisional correlation of certain surfaces does not seem justified.

[3] D. F. Hewett, "The Heart Mountain Overthrust, Wyoming," *Jour. Geol.*, Vol. XXVIII (1920), p. 537.

Range by numerous tributaries of Clark Fork affords a partial view of the topography upon which the volcanoes accumulated, and gives some measure of the amount of prior denudation in that area. These volcanics now rest on strata as old as Upper Cambrian, and presumably once extended far beyond Clark Fork on to the pre-Cambrian granite. Thus pre-Upper Miocene dissection amounted to several thousand feet. Furthermore, the exhumed surface along Clark Fork has in places a known relief of about 2,000 feet in less than 3 miles.[1] This topography on the southwest flank of the Beartooth Range signifies that either (1) the region was peneplaned, uplifted at least 2,000 feet, and in part deeply dissected before the Upper Miocene vulcanism; (2) much of the Beartooth Mountains had been worn down to an old-age plain whereas the southwestern portion had reached maturity only by this time; or (3) peneplanation and uplift occurred during some later epoch.

If only one peneplain existed in the Beartooth Mountains, it might be tentatively correlated with post-Miocene summit flats in the Absaroka Range, and thus would satisfy the last alternative. As will be apparent in discussion of the subsummit peneplain and younger features, this dating appears to be inadmissible. It is quite improbable that erosion of the huge obdurate mass of the Beartooth Range could have reached an old-age stage while weak shales and limestones on its lower flanks contained deep valleys. Hence the first alternative appears to be the most satisfactory interpretation. This indicates an Oligocene or early Miocene age for the summit peneplain. It may be that the old-age aspect of the region was retained until the episode of Middle Miocene deformation, which appears to have affected widely the northern Rocky Mountains. As a result of this uplift the topography beneath the volcanics is presumed to have been carved from the elevated plain.

This interpretation appears to have some corroboration in the diastrophic and gradational history of other front ranges to the north and the adjoining Great Plains. On this basis the planation, uplift, and renewed dissection of the Beartooth Mountains should

[1] Note the contact of this breccia with the underlying Paleozoics on the southwest slope of Hunter Peak, as shown on the areal geology sheet of the Crandall quadrangle, Absaroka, Wyoming, folio, *U.S. Geol. Survey, Geol. Atlas*, No. 52.

have occurred between Middle Eocene and late Miocene. Such denudation should be recorded somewhere in the sediments of the Great Plains, but unfortunately no known Tertiary deposits that postdate the Beartooth overthrust remain on the western plains of Montana. The Linley conglomerate, a local deposit of unknown age, about 10 miles northwest of Red Lodge, contains pebbles from the Paleozoic limestones and the pre-Cambrian crystalline core of the range. It lies unconformably on beveled Fort Union beds. This formation may afford some clue to the date of planation, but until diagnostic fossils are discovered, it may represent any post-Middle Eocene epoch.

The deformed Fort Union and underlying formations on the adjacent plains were truncated, and this erosional plain was covered by gravels which do not appear to be older than Pleistocene or late Tertiary. It is inherently probable that higher and older surfaces than those now preserved upon the plains were formed and covered with detritus from the range. Such alluvial deposits may have been essentially correlative with Oligocene strata which have been partially preserved at Cypress Hills, far out upon the plains of Southern Canada,[1] but this is conjectural.

Another possible source of pertinent data is along the Rocky Mountain front immediately north of the Beartooth Range. Over the Great Plains between the Little Belt and Beartooth mountains, erosion has planed across a folded terrane which includes the Livingston formation.[2] The upper part of this formation has been interpreted to be of Fort Union age.[3] Bozeman "lake beds" lie on pre-Cambrian granite at the south end of the Bridger Range, about 20 miles west of the northwestern end of the Beartooth Range. Little is

[1] Information in regard to these deposits is briefly summarized, and original references given, by Collier and Thom, "The Flaxville Gravel and Its Relation to Other Terrace Gravels of the Northern Great Plains," *U.S. Geol. Survey, Prof. Paper 108* (1918), p. 183.

[2] See the structure sections of the Little Belt Mountains folio, *U.S. Geol. Survey, Geol. Atlas*, No. 56.

[3] R. W. Stone and W. R. Calvert, "Stratigraphic Relations of the Livingston Formation, Montana," *Econ. Geol.*, Vol. V (1910), p. 752.

W. T. Thom, Jr., and C. E. Dobbin, "Stratigraphy of Cretaceous-Eocene Transition Beds in Eastern Montana and the Dakotas," *Bull. Geol. Soc. Amer.*, Vol. XXXV (1924), Fig. 2, p. 484.

known about the actual form of the surface beneath these sediments in the adjacent Gallatin Valley, but it cuts across formations ranging from Archean to Cretaceous. Vertebrate fossils show these beds to be Middle Miocene.[1] Similar sediments, designated Deep (Smith) River beds, occupy a broad basin southwest of the Little Belt Mountains. The southernmost occurrence is about 50 miles north of the Beartooth Range, along the east flank of the Big Belt Mountains. A considerable number of mammalian remains determine the lower beds (Fort Logan) to be Upper Oligocene or Lower Miocene.[2] These deposits overlap from the Livingston to the Spokane formation (Proterozoic) in a distance of 4 miles. The erosion surface which bevels the folded formations of the plains and the bordering portions of the front ranges appears to pass under these sediments; consequently, it would be of pre-Miocene age. It was presumably on this basis that Weed stated: "At the close of the Eocene [Oligocene?] period the entire quadrangle was reduced to a gently hilly country bordered by a broad level plain."[3]

No means exist of directly correlating this surface with erosion levels in the Beartooth Mountains, but it is highly significant that a much more extensive region, embracing both plains and mountains, was reduced to a gently undulating plain prior to the early Miocene. Thus the correlation of the summit peneplain with this surface seems justified, at least as a working hypothesis.

Determination of the age of summit peneplains in related districts of the northern Rocky Mountains may afford some clue to the solution of the local problem. As the result of extensive field study of the mountain ranges of central western Wyoming, and from a careful scrutiny of the evidence presented by geologists working elsewhere within the province, Blackwelder concludes that "the evidence from all points of view here considered, although it does

[1] Earl Douglass, "Fossil Mammalia of the White River Beds of Montana," *Trans. Amer. Phil. Soc.*, N.S., Vol. XX (1902), map on p. 241.

[2] W. B. Scott, "The Mammalia of the Deep River Beds," *ibid.*, Vol. XVIII (1896), p. 60.

W. D. Matthew, "Cenozoic Mammal Horizons of Western North America," *U.S. Geol. Survey Bull. 361* (1909), p. 112.

[3] W. H. Weed, "Geologic History," Little Belt Mountains folio, *U.S. Geol. Survey, Geol. Atlas 56* (1899), p. 7.

not establish the age of the [Wind River] peneplain, does strongly indicate that it was Pliocene."[1]

On the other hand, it is the conviction of several geologists working in northern Idaho and western Montana that the summit peneplain in that region is certainly pre-Miocene, and probably is Eocene.[2] The evidence presented by Umpleby and Atwood has been reviewed by Blackwelder[3] and Rich[4] who conclude that the published data permit, and in some instances favor, the alternative interpretation that certain summit peneplains are late Miocene or Pliocene. Recent detailed field studies in southeastern Idaho lead Mansfield to conclude that the Snowdrift peneplain of that region is pre-Middle Miocene, and possibly Oligocene or Eocene.[5]

The published data indicate that the summit peneplains of the northern Rocky Mountains are of two distinct ages. The earlier one apparently was formed during the epochs between the main orogeny and widespread Miocene re-elevation, whereas the later one was developed after this regional uplift. Thus the Beartooth summit peneplain may have a possible correlative in one of these pre-Middle Miocene surfaces.

On the other hand, as suggested by Atwood and emphasized by Mansfield, widely separated districts of the northern Rocky Mountains may have had a quite dissimilar physiographic history. Thus

[1] Eliot Blackwelder, "Post-Cretaceous History of the Mountains of Central Western Wyoming," *Jour. Geol.*, Vol. XXIII (1915), p. 206.

[2] J. B. Umpleby, "An Old Erosion Surface in Idaho; Its Age and Value as a Datum Plane," *Jour. Geol.*, Vol. XX (1912), pp. 139–47.

W. W. Atwood, "The Physiographic Conditions at Butte, Montana, and Bingham, Utah, When the Copper Ores in These Districts Were Enriched," *Econ. Geol.*, Vol. XI (1916), pp. 697–740; "Physiographic Conditions and Copper Enrichment," *ibid.*, Vol. XII (1917), pp. 545–47.

Waldemar Lindgren, "The Idaho Peneplain," *ibid.*, Vol. XIII (1918), pp. 486–88.

D. C. Livingston, "The Idaho Peneplain," *ibid.*, pp. 488–92.

J. T. Pardee, "Ore Deposits of the Northwestern Part of the Garnet Range, Montana," *U.S. Geol. Survey Bull. 660* (1918), pp. 162–64.

[3] Eliot Blackwelder, "An Old Erosion Surface in Idaho: A Criticism," *Jour. Geol.*, Vol. XX (1912), pp. 410–14; "Physiographic Conditions and Copper Enrichment," *Econ. Geol.*, Vol. XII (1917), pp. 541–50.

[4] J. L. Rich, "An Old Erosion Surface in Idaho: Is It Eocene?" *ibid.*, Vol. XIII (1918), pp. 120–36.

[5] G. R. Mansfield, "Tertiary Planation in Idaho," *Jour. Geol.*, Vol. XXXII (1924), pp. 472–87.

the age of erosion surfaces in far distant areas may have so little bearing upon the dating of peneplains in the Beartooth Mountains that it would be somewhat hazardous, in the present state of knowledge, to correlate them. It is to be expected, however, that major diastrophic and erosional events in a closely related group of mountain ranges would be reflected in each of the units. The Beartooth peneplains undoubtedly are more closely related to erosion surfaces in the Absaroka Range and the Rocky Mountain–Great Plains tract to the north than to those much more distant, although some of the latter may be approximately contemporaneous.

Summarizing the discussion of the Beartooth summit peneplain: Its age cannot be positively established within narrow limits, either from local evidence or by correlation with other peneplains in the province. It is evident, however, that the post-Middle Eocene orogeny almost certainly precludes its being as old as Eocene; rather, a post-Eocene age is indicated. The subsummit peneplain and younger erosional features apparently make a late Tertiary age inadmissible. Partial contemporaneity with the Oligocene plain on Cypress Hills of the northern Great Plains is tentatively suggested. This view is sustained in some measure by the erosional surface beneath the Upper Miocene volcanics of the Absaroka Range. Additional support is afforded by the occurrence of early to Middle Miocene basin deposits on Paleocene (?) to pre-Cambrian rocks at the southern ends of the Bridger and Big Belt ranges. Finally, a presumably correlative surface, which seems to pass under these sediments, exists in the peneplain of the northerly adjoining Great Plains. These seem, therefore, to be credible bases for considering the Beartooth summit peneplain to be Oligocene.

Subsummit peneplain.—Several lines of evidence which bear upon the age of the subsummit peneplain indicate it to be Pliocene. There is some suggestion that it may have been only slightly dissected in the late Pliocene or very early Quaternary.[1] Features that should be considered in dating this surface are: (1) character of the plateau remnants; (2) its relation to the summit peneplain; (3) possible cor-

[1] The writer dissents from the view of Alden (see *Bull. Geol. Soc. Amer.*, Vol. XXXV [1924], pp. 396, 399) that this surface may be as old as Oligocene. While there may be some justification for considering it to be late Miocene, the available evidence presented in this paper indicates that it is not older than Pliocene.

relatives among other Rocky Mountain erosion surfaces, especially in the adjoining Absaroka Range; (4) depth and extent of valleys eroded in it; and (5) possible correlatives on the Great Plains.

1. It may be re-emphasized here that the large area of the flattish remnants is the most striking feature of the subsummit peneplain, in spite of its position 4,000–5,000 or more feet above the Great Plains, and the vigorous streams of steep gradients that have trenched it (Fig. 2). This aspect, taken in connection with the abrupt rise of the mountain front for 3,000–4,000 or more feet above the plains, and its comparatively slight dissection (Fig. 1), suggests strongly that the elevation and transection of the subsummit peneplain occurred somewhat recently, rather than far back in the Tertiary. But such inferences must be checked by other evidence.

2. The subsummit peneplain was produced in the cycle of uplift and erosion that followed the formation of the summit peneplain. As indicated previously in this discussion, the latter must be post-Middle Eocene, and probably is Oligocene. After that date the range was elevated approximately 2,000 feet, and again very largely peneplaned. The first appropriate time of widespread uplift in the Rocky Mountains seems to be the Middle Miocene. Thus both the erosional history of the Beartooth Range and the diastrophic record of the province suggest that the subsummit peneplain is post-Middle Miocene, and probably Pliocene.

3. During late Miocene time there existed, on the extreme southwestern slope of the Beartooth Range, a volcano whose *ejecta* apparently formed a cone of great height and with a broad base. Through a restoration of this volcanic peak by comparing it with a modern one (Mount Etna) of similar type and structure, Iddings estimated that at least 10,000 feet of material was eroded from it before the level of the present mountain crests was reached.[1] It was further calculated that this peak probably had a basal radius of 20 or more miles.

Inspection of the maps of Crandall Basin reveals that erosion of the former volcanic peak resulted in a somewhat flattish plateau (Hurricane Mesa), which now has a maximum altitude of about 10,-

[1] J. P. Iddings, "The Dissected Volcano of Crandall Basin," *U.S. Geol. Survey, Mon. 32*, Part II (1899), p. 236.

600 feet, and that this erosion surface was developed across the broad core of coarse gabbro as well as upon the surrounding breccias.[1] Although this plateau may coincide in part with almost horizontal lavas, the removal of even a few thousand feet of volcanics and truncation of the Crandall cone and plug at this level indicate that Hurricane Mesa is a remnant of a former erosion surface of moderate or low relief. This surface doubtlessly was once quite extensive, but subsequent uplift of the region caused its destruction on the weaker breccias.

Other remnants of this erosion surface may exist farther south in the Absaroka Range on denuded Upper Miocene intrusions in Sunlight Mining Region, at Eagle Nest, and on the southwest spur of Wapiti Ridge, although the evidence is less conclusive than at Hurricane Mesa.[2] If these flattish ridge crests on intrusive masses and contiguous breccias should be due to peneplanation of the region, some of the mesas at accordant elevations on almost horizontal lavas may be of the same origin, but obviously this cannot be demonstrated.

The Beartooth summit plateau is the apparent continuation of Hurricane Mesa. Evidence presented in this article makes it very doubtful that both the summit and subsummit peneplains are post-Miocene. Hence the presumptive correlation of the surface on Hurricane Mesa is with the subsummit peneplain, making the latter post-Miocene in age.

In considering this correlation it should be noted that the subsummit plateau on the southwestern slope of the Beartooth Mountains has in places an altitude of about 11,000 feet as compared with 10,600 feet on Hurricane Mesa. Furthermore, it is improbable that the resistant mass of the Beartooth Range could have been planed at a lower level than is represented in Hurricane Mesa without much greater erosion of the Absaroka volcanics. Under the circumstances no other correlation seems possible. This implies that the Beartooth Range was tilted southwesterly between the two epochs of peneplanation, so that the earlier surface now passes below the horizon

[1] *Ibid.*, Plates XXXI and XXXII.

[2] See the areal geology maps in the Absaroka, Wyoming, folio, *U.S. Geol. Survey, Geol. Atlas*, No. 52.

of the later one and beneath the volcanics. Such tilting is not only inherently probable but is indicated by the southwesterly dip of the summit plateau, whose projected surface passes beneath the volcanics in the Absaroka Range.

Definite correlation with more distant peneplains is not attempted at this time, because of some uncertainty in regard to their age. It should be recalled, however, that many other planed surfaces in the province are considered to be late Miocene or Pliocene.[1]

4. Sharp canyons have been eroded several thousand feet below the subsummit plateau but they do not provide a reliable measure of the time that has elapsed since the uplift. There seems to be no reason per se why this canyon-cutting could not have been done mainly in the Quaternary, especially since glacial erosion was a large factor in the process.

Somewhat better evidence is given by Clark Fork Valley, along the southern and southwestern sides of the plateau. For several miles above the mouth of the canyon the river flows in a sharp inner canyon which is trenched in an older valley floor (Figs. 7, 8, and 9). The latter is about 1,000 feet above the stream, and lies 2,000–3,000 feet below the subsummit plateau. It is clear that Clark Fork halted in its down-cutting long enough to carve a valley of noteworthy width then, upon being rejuvenated, sharply incised its course.

The obvious interpretation of these features is to ascribe them to two episodes of vertical uplift of the range with the interposition of considerable time. On this assumption it follows that the old valley may be due to uplift in middle or late Pliocene, and the inner canyon to uplift near the close of the Pliocene or early in the Quaternary. This problem needs more thorough field study, but the time allotted for the erosion of these valleys seems ample, especially in view of certain other features to be described. Although the high-level valley is about 2 miles wide at its mouth (Fig. 7), and slightly more than 3 miles wide above the mouth of Russell Creek (Fig. 8), it is rather sharply constricted just below the great bend in Clark Fork. At this place, where apparently the entire left wall of the canyon is

[1] See C. L. Baker, *Bull. Geol. Soc. Amer.*, Vol. XXIII (1912), p. 73; Eliot Blackwelder, *op. cit.;* J. P. Buwalda, *Science*, Vol. LX (1924), pp. 572–73; R. T. Chamberlin, *Jour. Geol.*, Vol. XXVII (1919), p. 161; W. M. Davis, *Ann. Assoc. Amer. Geog.*, Vol. I(1911), p. 31.

pre-Cambrian gneiss and granite, the only bench occurs on the right (south) side at or near the contact of the almost horizontal Cambrian and the underlying crystallines. The wider portions of the valley floor are either cut in Paleozoic limestones and shales, or are along the contact of these strata with the pre-Cambrian (Fig. 9).[1] The much broader valley above Crandall Creek is due in considerable

FIG. 7.—Mouth of Clark Fork Canyon. The high-level valley on the south (right) wall is cut to the contact of Paleozoic limestones and shales with pre-Cambrian granite. The edge of the subsummit plateau is shown above the left wall of the canyon. Drift of Clark Fork glacier occupies the foreground.

part to profound glaciation. Furthermore, the abrupt rise of the pre-Cambrian for more than 2,000 feet above the almost horizontal early Paleozoics on the northeast side of Clark Fork demonstrates the existence of a fault which has influenced the excavation of this valley (Fig. 8). Although it was too dark to see the features clearly when the writer came to the lower part of the old valley, it appears that the Paleozoics on the south wall may have once abutted against

[1] See also *Bull. Geol. Soc. Amer.*, Vol. XXXV (1924), Plates XVII and XVIII (opposite pp. 405 and 407).

the opposite wall of pre-Cambrian granite. Owing to the lack of positive evidence the point may not be stressed at this time, but the writer has suspected that the lower canyon of Clark Fork may be controlled in part by faults. No decisive evidence of faulting was observed, however, at the mouth of the canyon. It is probable, moreover, that huge glaciers, during two or more stages of glacia-

FIG. 8.—Floor of Clark Fork high-level valley. It is on almost horizontal Cambrian beds. Pre-Cambrian granite rises beyond the Clark Fork fault to the subsummit plateau. It is about 2,500 feet above the old valley floor and 4,000 feet above the river at the foot of the steep slope.

tion, greatly widened this valley in the limestones and shales, and stripped them from their pre-Cambrian base.

Other valleys of the range do not have similar high-level floors, but this is probably due to the fact that, except for a narrow zone at the canyon mouths, they are eroded in pre-Cambrian crystallines. Stillwater Valley furnishes suggestions of halts in its down-cutting, but these breaks in the profile may be the result of stages of glaciation or other factors.

From this discussion it is evident that less time was needed for

the erosion of the Clark Fork high-level valley than appears at first thought to be demanded. This valley, in its pre-glacial form, was excavated rapidly under especially favorable conditions, during an uplift which seems to have been comparatively rapid. The narrow-

FIG. 9.—Inner canyon of Clark Fork. It is cut about 1,000 feet below the high-level valley floor, which is at the contact of horizontal Cambrian beds (right background) and pre-Cambrian granite. The pre-Cambrian mass of the range is in the rear beyond the Clark Fork fault.

ness of all the canyons in proportion to their great depth, and the fact that the broad, flattish uplands extend to the margins of these canyons, indicate the great supremacy of uplift and down-cutting over lateral erosion. Hence it seems reasonable to conclude that the subsummit peneplain might have retained its essential character

until rapid late Pliocene uplift induced its dissection. Furthermore, there are hints in the steepening of the slope of the subsummit plateau toward its plainsward edge, and in the occurrence of large bowlders at high levels far beyond the range, that widespread nivation or very early glaciation may have affected the rising plateau. Should this surmise be true, it is possible that the subsummit surface may have been in general but slightly dissected by relatively shallow valleys at the dawn of the Quaternary. This must, however, remain in the field of conjecture for the present.

5. The great denudation which resulted in the Beartooth subsummit peneplain must have been recorded also far out on the Great Plains. Although the region has since undergone considerable uplift and dissection, this record may have escaped destruction in some places. Favorable sites for its preservation are on the broad high divides in the Yellowstone drainage system, where remnants of the old erosional surface and overlying deposits might occur.

An opportunity has not been available for extending these studies beyond the Beartooth Range, except for casual observations made during a rapid reconnaissance survey of the western plains and the front ranges for the Montana Bureau of Mines. The highest flattish divides along Yellowstone River far out on the plains and its main tributaries from the range are commonly covered by thick deposits of gravel,[1] which lie upon a broad erosional plain. The age of these gravels is unknown, but they appear to be late Tertiary or possibly early Quaternary. Their time relation to the erosion of the Beartooth Mountains is uncertain, but they may have been derived from the range as it was uplifted after the formation of the subsummit peneplain. Or, possibly, they may have been in part let down from earlier deposits made at higher levels during erosion of the range.[2]

[1] G. S. Rogers, "Geology and Coal Resources of the Area Southwest of Custer, Yellowstone and Bighorn Counties, Montana," *U.S. Geol. Survey Bull. 541–H* (1914), p. 31.

E. T. Hancock, "Geology and Oil and Gas Prospects of the Huntley Field, Montana," *ibid., Bull. 711* (1920), p. 128.

W. R. Calvert, "Geology of the Upper Stillwater Basin, Stillwater and Carbon Counties, Montana," *ibid., Bull. 641* (1916), Plate XXI (opposite p. 202).

[2] The relation of these terraces and their gravels to erosion of the mountains presents an interesting problem, but lack of space prevents its discussion here.

The Flaxville plain of northeastern Montana, whose gravels contain remains of Pliocene vertebrates,[1] may be part of an extensive erosional surface which was formed over the Montana plains during a portion of the cycle that resulted in the Beartooth subsummit peneplain, but again this is at present conjectural.[2] Former erosion levels exist in some other front ranges to the north, but their age has not been determined, although there are suggestions of comparatively recent uplift and dissection of extensive erosional surfaces.[3]

In review, these points bear on the age of the subsummit peneplain: (1) Middle (?) Miocene uplift caused dissection of the summit peneplain; (2) an Upper Miocene volcano and its lavas as well as certain intrusions were truncated; (3) the Clark Fork high-level valley was formed during uplift of the subsummit peneplain; (4) this valley was eroded rapidly by streams, and possibly by early Pleistocene glaciers, and owes its form in part to recent glaciation; (5) the sharpness of all the canyons, the abruptness of the mountain front below the plainsward margin of the subsummit plateau, and the slight dissection of the latter suggest comparatively recent rapid uplift of the range. Hence the subsummit peneplain is considered to be of Pliocene age; possibly it retained its essential characteristics until late in the period.

The events following peneplanation, as now interpreted, may be briefly summarized. Late Pliocene uplift renewed stream erosion, with Clark Fork making its high-level valley. These young valleys may have contained pre-Wisconsin glaciers, of which there are some

[1] A. J. Collier and W. T. Thom, Jr., "The Flaxville Gravel and Its Relation to Other Terrace Gravels of the Northern Great Plains," *U.S. Geol. Survey, Prof. Paper 108* (1918), pp. 179–84.

[2] For a brief statement of a different view, see W. C. Alden, "Physiographic Development of the Northern Great Plains," *Bull. Geol. Soc. Amer.*, Vol. XXXV (1924), pp. 385–424 (see pp. 396, 399, and 404).

Dr. Alden states that it is "unlikely that the Beartooth subsummit plateau is younger than Miocene, even if it is not so old as Oligocene" (p. 399). He bases this conclusion apparently on somewhat uncertain correlation of the Flaxville Plain with the uppermost terrace beyond the Beartooth Mountains and with the Clark Fork high-level valley. In view of the lack of evidence in proof of the Miocene age of the subsummit peneplain or of adequate disproof of its Pliocene age, as well as the evidence discussed in the present paper, it appears that this interpretation is not valid.

[3] Note the accordance of summits on some of the parallel ridges eroded from the thrust-fault blocks of the front range in the Saypo and Coopers Lake quadrangles.

suggestions. Later uplifts caused erosion of the inner Clark Fork Canyon and continued deepening of the other canyons. Prior to the advance of early Wisconsin glaciers, a series of terraces was developed beyond the mountain front. The uppermost terrace (Roscoe) may be late Tertiary or early Quaternary. An extensive intermediate terrace (Red Lodge) considerably antedates the Wisconsin epoch. A lower terrace (Rosebud) is also probably pre-Wisconsin. The last notable event was profound glaciation during the two Wisconsin stages. Whether uplift intervened between these stages or followed the later one has not been certainly determined.

SUMMARY

The salient points in the preceding discussion are:

1. The Beartooth Range contains two extensive erosion surfaces which are most probably peneplains. The summit peneplain is more than 12,000 feet above sea-level, and the subsummit peneplain is commonly about 2,000 feet lower.

2. An analysis of several lines of evidence leads to the conclusion that the summit peneplain is most probably Oligocene.

3. The subsummit peneplain is interpreted to be Pliocene. It may have been but slightly dissected late in the period, or, possibly, even in early Quaternary time.

4. The range was uplifted several times. These episodes were: (*a*) the climacteric orogeny which produced the ancestral range and the Beartooth overthrust in post-Middle Eocene time; (*b*) Middle (?) Miocene vertical uplift of about 2,000 feet; (*c*) late (?) Pliocene or early Quaternary (?) vertical uplift of a few thousand feet; and (*d*) Quaternary uplift, possibly at more than one time.

THE POST-MONTEREY DISTURBANCE IN THE SALINAS VALLEY, CALIFORNIA[1]

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ABSTRACT

Because of the supposed occurrence of an important angular unconformity at the top of the Monterey shale, most writers on the Tertiary geology of the central Coast ranges have inferred that mountain-making occurred in this region during the Miocene. A re-examination of all the localities that have been cited as showing the unconformity, and of many others in all parts of the region supposed to show it best, proves that the unconformity is purely erosional. Other types of evidence are discussed and the conclusion is reached that no mountain-making took place in this area at the close of Monterey shale deposition.

INTRODUCTION

The three commonly recognized divisions of the California Miocene, the Vaqueros, Monterey, and Santa Margarita formations, owe their names and type localities to the Salinas Valley region. The relation of the Vaqueros to the Monterey formation in this region has always been and still is a matter of controversy; the relation of the other two, however, has been until recently a matter of almost complete agreement. The nature of currently accepted views may be gathered from the following, selected from a large number of similar passages in the literature:

> Elevation occurred and the Monterey shale was folded, and in local areas sharply contorted. . . . . A period of prolonged erosion intervened after the elevation of the Monterey shale before subsidence again overtook the region [San Luis Quadrangle] and the middle Neocene (Pismo and Santa Margarita formations) began to be formed. . . . . It thus appears that with the post-Monterey deformation the position of the present mountain ranges and valleys was in large part determined.[2]

[1] To R. E. Collom, chief geologist of the Marland Oil Company of California, I am indebted for permission to publish this paper. W. D. Kleinpell, C. Cassel, and I. Moody, geologists for the same company, contributed efficiently to the field work upon which the paper is based. Many other geologists have assisted, chiefly by vigorous criticism of the ideas here presented.

[2] H. W. Fairbanks, *The San Luis Folio* (1904), p. 10.

> One of the most widespread and important periods of diastrophism in the Tertiary history of the Pacific Coast was that immediately following the deposition of the Monterey or lower middle Miocene . . . . Faulting on a most magnificent scale took place along the earthquake rift and certain other fault zones, especially that in the Salinas Valley. . . . . [1]
>
> In the Salinas Valley region it is not uncommon to find the difference in dip between the Temblor [Monterey] and the Santa Margarita as much as 30° to 90°, together with marked difference in strike. . . . . It is interesting to note that only a comparatively short distance to the east of the southern Salinas Valley area, where the great unconformity between the Temblor and the Santa Margarita deposits is best seen, it has been very difficult to find the line separating these two horizons.[2]

These passages will serve to show how widespread is the view that a profound angular unconformity exists at the base of the Santa Margarita formation; that the disturbance inferred from the alleged unconformity was the cause of many of the complex conditions now existing in the Coast ranges; and that the very center of diastrophic activity, the place where its results are most obvious and least mistakable, is the southern Salinas Valley. In this paper I shall attempt to show, on the contrary, that the unconformity in question, at least in the southern Salinas Valley, is a purely erosional one of comparatively unimportant character; and that the post-Monterey disturbance was probably one of the very mildest of several that occurred in the region of the Coast ranges during the Tertiary period.

GEOLOGY OF THE SOUTHERN SALINAS VALLEY

Despite the complex details, the general geological relations of the central Coast ranges are fairly simple. The accompanying sketch map (Fig. 1) shows many of them at a glance. The most important fact of all is that the region consists of a much-fractured, granite-based plateau, bounded east and west by folded ranges of shale and serpentine. The granite of the central area protrudes in many scattered localities, and outcrops broadly in the mountains both north and south of the Paso Robles Basin: the La Panza Range, the Gabilan and Palo Escrito ranges, and the high mountains near

[1] Ralph Arnold, in Willis *et al.*, *Outlines of Geology* (1910), p. 241.

[2] B. L. Clark, "The Marine Tertiary of the West Coast," *Journal of Geology*, Vol. XXIX (1921), pp. 602, 603.

Junipero Serra Peak. The basin is divided into two fairly equivalent areas by a fault zone, the King City fault, which is followed by the Salinas River. The eastern, more typically plateau-like portion

FIG. 1.—Index map of a part of the central coast ranges

will here be called the Gabilan Mesa. The western division is the Santa Lucia foothills. East of the San Andreas fault, often called the "earthquake rift," lies the Diablo Range; west of the fault zone parallel to the Nacimiento River rises the main Santa Lucia Range.

In the Paso Robles Basin, as thus defined, occur the Miocene strata which are the subject of this article. Along the western margin of the basin they are associated with Cretaceous shale and sandstone, and with a thick series of unfossiliferous conglomerate and sandstone of uncertain age. In the northwestern part of the area these pre-Miocene strata include a considerable amount of black shale in which have been found fossils considered to be Martinez (Lower Eocene) in age.[1] Over much of the basin, however, the Miocene strata appear to rest on the granite itself. The Vaqueros formation is probably limited to the western half of the area, and even the Monterey may be missing from much of the Gabilan Mesa. Over the eastern part of the basin the Santa Margarita formation occurs, overlain in part by marine strata variously classed as latest Miocene or earliest Pliocene, here called the Poncho Rico formation; and by a non-marine Pliocene formation, the Paso Robles, which at its maximum probably exceeds a thousand feet in thickness.

The marginal portions of the central Coast ranges, the Diablo and Santa Lucia ranges, are strikingly different in stratigraphy from the middle portion, but so similar to each other that a description of one will serve fairly well for both. The Diablo Range, for example, has no granite anywhere observable; its basement rock consists of easily deformable serpentine, along with shale, chert, and sandstone of the Franciscan (Jurassic?) formation. Cretaceous shale and sandstone aggregate several miles in thickness. The interbedded conglomerate consists, as one might surmise, very largely of granite pebbles. Marine Eocene and Oligocene strata are well developed, and the Miocene and Pliocene, like the Cretaceous, have a thickness measured in miles.

The more carefully one studies the geology of the basin, the more obvious it becomes that the surface structure is closely related to fractures in the granite basement. Even the complicated folding that has been described[2] in the Monterey shale is local, and is related to zones of faulting. Simple, unfractured folds are almost nonexistent in most of the area. In the Santa Lucia foothills the fault zones are especially numerous and complicated.

The history implied by the structure and stratigraphy of the

[1] B. L. Clark, oral communication.

[2] Whitney, *Geology of California* (1861), pp. 155, 156.

central Coast ranges cannot, of course, be elaborated here. The suggestion is obvious, however, that the granite mass was a land area during Mesozoic and early Tertiary time, and that when it sank the western half went down first and received the thickest coating of sediments. The Miocene and later history will be sketched on a later page.

THE EVIDENCE

EXPOSURES OF THE CONTACT

In the literature of Coast Range geology, as suggested above, the idea that the Monterey–Santa Margarita contact is an angular unconformity seems never to have been questioned. The evidence cited in favor of this far-reaching conclusion is, however, nearly all indirect. Little of it has been derived from an examination of the actual contact of the shale with the overlying sandstone. A presentation of the evidence now available may therefore appropriately begin with a brief description of some well-distributed outcrops in which the nature of the contact may be easily studied. Table I contains the exact location and a concise description of many of them in all parts of the southern Salinas Valley. Since observers sometimes disagree as to the interpretation even of excellent outcrops, nearly all those here listed have been independently examined by more than one geologist.

Several of these outcrops are found along some of the most disturbed zones in the whole area. In two of them the Santa Margarita beds are overturned. Even in such localities, angular discordance is too slight to be seen. The outcrops show either a gradation from one formation to the other or, more commonly, a sharp, lithologic change. In some there is even a basal conglomerate a few inches thick; in others, mollusk borings occur in the upper surface of the older formation; and, in a few, the basal beds of the Santa Margarita sandstone are absent, or even the whole formation. Even when Poncho Rico strata rest upon the shale, however, no angular discordance can be seen.

Three of the areas listed in the table have been chosen for more detailed description. One of them is between Bradley and San Ardo, in the west bank of the Salinas River, near the Coast Highway; another is in the vicinity of the Nacimiento syncline, several

TABLE I

EXPOSURES OF SANTA MARGARITA–MONTEREY CONTACT

SOLEDAD QUADRANGLE:

1. South bank of Arroyo Seco Creek, a few hundred feet east of the new bridge; Sec. 16, T. 19 S., R. 6 E. Transition from diatomaceous shale to massive sandstone. No sharp break.
2. Steep bluff south of Arroyo Seco, 4 miles west of the last, on section line between Secs. 24 and 25, T. 19 S., R. 5 E. Soft, white sand on diatomaceous shale, sharp contact, rare basal pebbles, no discordance of dip.
3. Near outer edge of basin-like Reliz syncline, 2 miles up Reliz Canyon, T. 19 S., R. 6 E. Partly in Junipero Serra quadrangle. No angular discordance, chert pebbles locally in base of sandstone; in some places a transition series.

KING CITY QUADRANGLE:

4. Near Thompson gulch, northwest quarter of northwest quarter of Sec. 14, T. 20 S., R. 7 E. Pholas-bored chert pebbles in base of ashy sands under typical Santa Margarita sandstone.
5. Along Jolon road at south edge of Sec. 35, T. 21 S., R. 7 E. Like last, but erosion plane high in ashy series.

BRADLEY QUADRANGLE:

6. Bank of Salinas River near Coast Highway, between Secs. 14 and 15, T. 23 S., R. 10 E. Both formations vertical; sharp, lithologic break; pholas-borings (see fig. 2).
7. Stream bank near Pleyto well, southeast quarter of Sec. 26, T. 24 S., R. 10 E. No visible discordance; sharp change in lithology.
8. Sulphur Canyon, Sec. 3, T. 25 S., R. 10 E. Lithologic break only.
9. North bank of San Antonio River, Sec. 29, T. 24 S., R. 10 E. Same as last, but sand appears to be Upper Santa Margarita or possibly Poncho Rico.
10. Same, Sec. 34, T. 24 S., R. 10 E. Poncho Rico(?) on Monterey disconformably, Paso Robles on both with angular contact; oil at contact.

ADELAIDA QUADRANGLE:

11. In a deep canyon, southwest quarter of northeast quarter of Sec. 24, T. 25 S., R. 10 E. Conditions like those in Sulphur Canyon.

BRYSON QUADRANGLE:

12. Along Copperhead Creek, northwest corner of northeast quarter of Sec. 18, T. 24 S., R. 9 E. Similar to the last.
13. Along Deer Creek, just west of abandoned house, southeast quarter of northeast quarter of Sec. 3, T. 24 S., R. 8 E. Erosion plane with shale pebbles in midst of soft, ashy transition series.
14. Along road near crossing of San Antonio, Sec. 35, T. 23 S., R. 8 E.

POZO QUADRANGLE:

15. Secs. 19 and 20, T. 28 S., R. 15 E. Discussed in text.

miles west of San Miguel; and the third is on the north slope of the La Panza Range, about 25 miles southeast of Paso Robles. Together these three areas cover the southern Salinas Valley region fairly well. Each of them, furthermore, has been considered by one or more earlier workers to show evidence of a marked angular unconformity.

THE SAN ARDO REGION

Speaking of the San Ardo region, English states: "The Santa Margarita beds overlie the shale in this belt with marked uncon-

FIG. 2.—The Monterey-Santa Margarita contact north of Bradley, in Salinas River bank.

formity."[1] A detailed examination of this area has discovered several places at which the contact can be seen. In most cases the unconformity is indicated only by the presence of a change in lithology and by rare pebbles of shale in the base of the upper formation. Toward the north there is between the two formations a transition series of soft, fine-grained sandstone, ash, and impure diatomite, with or without an erosion plane at the base, middle, or top. In the exposure figured (Fig. 2), there are no transition strata and no pebbles, but there is a well-defined lithologic change. There are

[1] W. A. English, "Geology and Oil Prospects of the Salinas Valley-Parkfield Area, California," *U.S. Geol. Surv. Bull. 691-H* (1918), p. 245.

also pholas-borings in the upper surface of the shale, many square feet of which can be seen in the river bank. The photograph shows clearly the absence of angular discordance between the nearly vertical strata of the two formations. No outcrop in this general area shows any trace of discordance between them, and in no locality do the field relations suggest the presence of more discordance than can be seen.

THE NACIMIENTO SYNCLINE

Referring to the Nacimiento area, Nomland writes:

> The unconformity between these formations in this vicinity is very marked, so that while the Monterey has been intensely folded and faulted, the overlying Santa Margarita has relatively gentle dips.[1]

With this opinion many other geologists have agreed.[2] Certainly there are many features in the locality that seem to confirm it. In the big bend of the Nacimiento River, west of the Nacimiento ranchhouse, for example, the Monterey strata are broken and contorted to an extreme degree. Above them on the mountain side gently dipping beds of Santa Margarita sandstone may be seen. The evidence appears convincing until one discovers that the contorted strata occur along a prominent fault zone, traceable both north and south of this locality for many miles. This fact suggests the desirability of searching for the actual contact of the two formations, preferably a short distance away from the fault. A half-mile to the west, across the Nacimiento syncline, the conditions are right and the contact is well exposed. Here one finds, as usual, that the basal stratum of the sandstone dips as steeply as the underlying beds of shale. A mile or two north of the river, in Sulphur Canyon, the contact, still accordant, may be seen again. This exposure is particularly interesting in view of the "relatively gentle dips" supposed to characterize the Santa Margarita strata in this area. They are here overturned.

[1] J. O. Nomland, "Fauna of the Santa Margarita Beds in the North Coalinga Region of California," *Univ. Cal. Pub. Geology*, Vol. X (1917), p. 304.

[2] It is interesting to note that a party under State Geologist Whitney examined this locality about sixty years ago and found that the sandstone strata were "apparently conformable" with those of the bituminous shale, now called Monterey. J. D. Whitney, *Geology of California*, Vol. I (1865), p. 146.

THE HIGHLAND MONOCLINE

The third area chosen for detailed description is a small anticline which interrupts the Highland monocline on the north flank of the La Panza Range. In this region a 4,000-foot sandstone series underlies the foraminiferal shale of the Monterey, which is about 1,000 feet thick. In its upper part the latter formation includes many thin strata of compact opal alternating with beds of diatomite and powdery foraminiferal shale. This series is overlain by a marine ash bed a few feet thick, which has been taken as the dividing-line between the Monterey and Santa Margarita formations. Above it are silt and shale, and a little higher, beds of massive sandstone, some of which contain Santa Margarita fossils. Over most of the region there can be little doubt that the silt rock and shale above the opalized zone constitute a transition series between the two formations. In the anticline mentioned above, however, the conditions have suggested the presence of an angular unconformity. The favorable evidence is that the anticline forms a hill the highest part of which is capped by one of the beds of hard sandstone, dipping about 5°. Below it in the hillside Monterey strata dip 45°. The area has been examined several times for evidence bearing on the existence of an unconformity, and the relevant data secured may now be summarized. First, the transitional series is present in the anticline as elsewhere. Even the ash bed occurs in its full thickness. It is difficult to harmonize this fact with the occurrence of a post-folding erosion interval before the deposition of the sandstone. Secondly, the steep dips in the shale on the hillside give place to much gentler dips toward the top of the hill. In a traverse carried across the anticline the lowest dip actually measured was 2°. It was found in one of the uppermost beds of diatomaceous shale. So far as they are now known, then, the conditions in this area, like those in the localities previously discussed, are not inconsistent with the idea that forms the main thesis of this paper, namely, that angular discordance at the Monterey–Santa Margarita contact is non-existent or at least very rare in the southern Salinas Valley.

CONDITIONS OUTSIDE OF THE SALINAS VALLEY

To conclude the discussion of direct evidence some attention will be given to conditions in areas adjacent to the Salinas Valley. In two of them competent observers have found what they describe

as actually discordant contacts between the Monterey and Santa Margarita formations or their equivalents. One of them is in Waltham Valley, in the Diablo Range, between the Temblor sandstone and the overlying Santa Margarita formation, which is here composed chiefly of siliceous shale. The visible discordance appears to be limited to a single outcrop.[1] The contact of the two formations can be traced for 40 miles or more to the southeast but shows no discordance anywhere else. A few miles northwest of the exposure in question, moreover, along Lewis Creek, the discoverers of the discordant contact were themselves unable[2] even to find a dividing-line between the two formations.

The other locality in which angular discordance has actually been seen is in the San Luis quadrangle, south of the Paso Robles Basin. It is well known that Fairbanks found there abundant evidence of several kinds tending to show the existence of a marked angular unconformity at the top of the Monterey shale.[3] That a part of his observations are susceptible of a different interpretation, however, there is already some proof. In a structure section which meets the seacoast a few miles northwest of Pismo, for example, he shows a discordance of nearly 90° between the Monterey shale strata and those of the overlying sandstone, considered to be equivalent to the Santa Margarita. Yet the accompanying photograph (Fig. 3), taken along the same coast and certainly not far from the same place, shows that the discordance, if it exists at all, is slight. That the San Luis quadrangle has other phenomena not too easily harmonized with the belief in a profound angular unconformity is suggested by a reading of the *Folio* text itself. Consider such passages as the following:

> At Paloma the Monterey shale has been closely folded and forced against the Santa Margarita formation so that both are overturned.
>
> At the point where they [two folds in the Monterey shale] pass beneath the sandstones of the Pismo formation [an equivalent of the Santa Margarita] they have been thrust against the latter, almost overturning them.[4]

[1] R. W. Pack and W. A. English, "Geology and Oil Prospects in Waltham, Priest, Bitterwater, and Peachtree Valleys, California," *U.S. Geol. Surv. Bull. 581–D* (1914), p. 131.

[2] R. W. Pack and W. A. English, *op. cit.*, p. 131.

[3] H. W. Fairbanks, *The San Luis Folio* (1904), pp. 8 ff. Also, same author, "Geology of a Portion of the Southern Coast Ranges," *Journal of Geology*, Vol. VI (1898), p. 564.

[4] *Op. cit.*, p. 8.

In each instance a reasonable alternative hypothesis would appear to be that the folding, forcing, and thrusting all took place in post-Santa Margarita time. Such considerations as these suggest that even in the Diablo and Santa Lucia ranges, the unconformity may be somewhat less pronounced than one would judge from the literature.

In spite of this possibility, however, the existence of some angular discordance in both Waltham Valley and the San Luis region is here taken for granted. Until someone subjects the upper surface

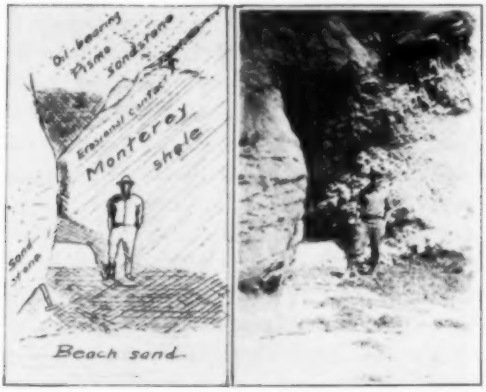

FIG. 3.—The Monterey-Pismo contact near Pismo, with sketch for key

of the Monterey shale of those regions to a more detailed study than any already made, there is no sufficient reason for doubting the correctness of the observations made by earlier investigators. The only question here raised is whether or not the conclusions drawn from some of those observations may not have been unduly sweeping, as was true in the Salinas Valley. At the same time, it may be noted again that the basement rock of both these regions is chiefly shale and serpentine. Such material, it may be, would permit some folding of the superposed strata during a disturbance that failed entirely to fold the granite-supported sediments of the Paso Robles Basin.

AVERAGE DIPS IN THE TWO FORMATIONS

A reference to the quotations in the introduction to this paper will show that, as evidence of the unconformity, great reliance seems to have been placed upon the presence of steeper dips in the Monterey shale. Such observations may appear to be, but are really not, similar to those reported in this paper. They do not refer, like the latter, to contiguous portions of the two formations in question, but rather to portions of each assumed to be representative. Such observations would never be expected to reveal an erosional unconformity. They simply furnish an easy if somewhat untrustworthy method of inferring angular discordance at a concealed contact. When the contact is discovered, however, and found to have no angular discordance whatever, the dip observations cease to imply anything about the conformity or non-conformity of the two formations. In the southern Salinas Valley therefore, the finding of perfectly accordant contacts of the Monterey and Santa Margarita formations in all the localities that have ever furnished dissimilar average dips would seem to constitute a complete and decisive refutation of all deductions drawn from such data.

It may be interesting and profitable, nevertheless, to pursue the subject a little farther to see why this particular type of indirect evidence has led in this region to such uniformly incorrect results. One possibly valid reason lies in the different reaction of the materials of the two formations to deforming stresses.[1] The thinly laminated, siliceous shale of the Monterey is much more subject to crumpling and intricate folding than are the massive sandstone beds of the Santa Margarita formation. It is suggestive to notice that in the Highland monocline much steeper dips can be found locally in the Monterey shale than any in the underlying massive sandstone of greater age.

A careful study of many localities in which differences of dip have led to results at variance with the actual nature of the contact suggests that the criterion is subject to one other serious source of weakness. In the summary of conditions in the Santa Lucia foothills

[1] C. K. Leith, *Structural Geology* (1923), p. 280.

mention has already been made of the several fault zones separated by broader areas of relatively simple structure. These fault zones are exactly the places where the older formations, including the Monterey shale, protrude most prominently through the younger strata, which lie little disturbed in the intervening areas. To a reconnaissance worker nothing seems more evident than that the greater deformation of the older strata is a general condition. Only detailed field work over a large area suffices to demonstrate that one has really been comparing slightly deformed portions of the younger formation with greatly deformed portions of the older.

The evidence from difference of deformation is perilous, then, for several reasons. No matter how strong it may sometimes appear, it is subject to complete refutation by such a study of the contact as has in this case been made. The criterion is weak, furthermore, when applied to formations composed of different materials; and is unsuited to a region having the structure that prevails in the Salinas Valley. It is, in short, a criterion hardly worthy of the trust that seems to have been reposed in it.

RELATIVE HARDNESS OF STRATA

After the Monterey epoch came the uplift and mountain-making of the Coast Ranges, hardening all the older Tertiary rocks, and inaugurating the modern topography of the State.[1]

During this time also [the post-Monterey diastrophic interval] the chief chemical change was wrought in the bituminous shales, for pebbles of the flinty altered shales occur at the base of the San Pablo [Santa Margarita] formation in exactly the same condition as the shales on which the formation rests.[2]

These passages illustrate a common belief, that the older Tertiary strata are in general noticeably harder than the post-Monterey formations. Is this belief valid? The best conclusion that can be drawn from numerous field observations in the Salinas Valley is that no such difference in hardness exists. Along the San Andreas rift and in other areas where it has been crushed, the Santa Margarita diatomaceous shale is very similar to the Monterey shale in similar situations. In the Gabilan Mesa the former material is very soft;

[1] J. P. Smith, "The Geologic Formations of California," *California State Mining Bureau Bull. 72* (1916), p. 37.

[2] H. W. Fairbanks, "Geology of a Portion of the Southern Coast Ranges," *Journal of Geology*, Vol. VI (1898), p. 564.

so is the latter in the Highland monocline. Some beds of the Santa Margarita sandstone are soft; others are hard and either siliceous or calcareous. Thoroughly silicified beds of sandstone and conglomerate occur even in the Paso Robles; other beds hardly cemented at all occur in the Vaqueros formation. In an instructive outcrop along Deer Creek in the Bryson quadrangle the erosional contact of the Monterey and Santa Margarita formations separates sandstones of similar texture. The lower stratum grades down into a great thickness of typical siliceous shale, which rests on fossiliferous Vaqueros sandstone. It certainly represents the Monterey formation. The upper bed, with a few Monterey pebbles at its base, has a Santa Margarita fauna. The conditions are thus unusually favorable for a comparison of similar materials above and below the unconformity. The comparison was made, but failed to discover any difference in hardness between them.

The idea that the Monterey chert, the "altered shale" of one of the passages above, dates from the post-Monterey folding episode deserves special mention. The occurrence of chert fragments in the basal bed of the Santa Margarita proves without much doubt that the hardening was pre–Santa Margarita; but was it post–Monterey? As one of the results of a detailed petrographic investigation, Davis has answered the question as follows:

> The cherts of the Monterey are not due to metamorphism, or silicification of diatomaceous earth or bituminous shales. . . . . The variations in lithologic types seen in the Monterey are not due to different stages of alteration, but are due to original variation in the nature of the material which was accumulating.[1]

With this conclusion from the petrography all the field evidence seems to me to be in perfect accord.

The discussion of relative hardness may, then, be summarized as follows. First, no notable general difference of hardness actually exists between the rocks above and below the unconformity. Secondly, the Monterey chert was hardened before the post–Monterey disturbance took place. Lastly, any hardening that may have been accomplished in any of the older strata during that disturbance is certainly indistinguishable from the hardening accomplished at many other times, both before and since.

[1] E. F. Davis, "The Radiolarian Cherts of the Franciscan Group," *Univ. Cal. Pub. Geology*, Vol. XI (1918), p. 298.

PALEONTOLOGICAL EVIDENCE

A third type of indirect evidence in regard to the importance of the unconformity involves the paleontologic break between the two formations. This break has been held to be consistent only with a great diastrophic period. No adequate discussion of the matter can be attempted here, but some of the considerations upon which a discussion must rest may be pointed out. In the first place, the fauna of the Monterey shale itself is small and peculiar, probably because of unusual conditions that existed in the Monterey Sea. A more normal marine fauna can sometimes be found in interbedded sandy strata, but the position of these with reference to the formation as a whole is often not clear. In some cases at least they are in its lower portion and therefore have a fauna that lived much longer ago than the Santa Margarita fauna. Secondly, the fauna of the Santa Margarita formation, at least in the Salinas Valley, is sadly in need of thorough collecting and critical study. It is all but certain that some of the forms described as Santa Margarita were collected from strata definitely younger than the typical Santa Margarita formation. The inclusion in the fauna of such forms must, of course, magnify the apparent break between the two formations. Lastly, it may be noted that no faunal break, no matter how profound it may prove to be, can ever disprove the thesis of this paper, which is that in the Salinas Valley the Santa Margarita formation does not rest on the Monterey shale with an angular unconformity. A great break might, of course, suggest a considerable physical disturbance other than that involved in the existence of diatomite-depositing conditions; but the center of the assumed disturbance might have been remote from the Salinas Valley.

THE LITHOLOGY OF THE POST-MONTEREY FORMATIONS

As a measure of the importance of the disturbance in the Salinas Valley and near it, there is available still another kind of indirect evidence which seems never yet to have been used. According to the usual conception of post-Monterey geologic history, some mountain ranges of Monterey shale were uplifted by folding and faulting and partly eroded away. A later transgression of the sea inaugurated the deposition of the Santa Margarita sandstone. What happened to the Monterey detritus that was eroded from the mountains during

the emergent interval? Possibly it may be assumed to have been carried entirely away from the California mainland and deposited deep in the Pacific Basin. Even so, it is difficult to believe that during this time all portions of the formation that had been raised above drainage level were completely removed. Unless this feat was accomplished, however, it is equally difficult to account for the fact that the Santa Margarita formation, save a very thin basal layer not everywhere present, is as thoroughly granitic in its composition as any other formation in the whole Tertiary section; or that even the overlying Poncho Rico formation has few pebbles of Monterey chert or shale except in its upper part. The assumption of the required amount of erosion and transportation during the post-Monterey emergent interval appears to be a very improbable one. The lithological data plainly suggest that mountains of Monterey shale developed gradually and probably first became an important feature of Coast Range topography in Paso Robles time.

HISTORY OF THE PASO ROBLES BASIN IN TERTIARY TIME

What actually happened at the close of Monterey deposition? What is the relation of what happened then to the general course

TABLE II

TERTIARY PALEOGEOGRAPHY IN THE SALINAS VALLEY

Stage	Detritus and Its Sources	Kind of Basin	How Ended
PASO ROBLES (PLIOCENE)	Monterey shale, Franciscan rocks, granite	Lakes and river flats	Faulting; draining of Paso Robles Basin
PONCHO RICO (MIOCENE-PLIOCENE)	Granite, Franciscan rocks, Monterey shale, chert	Shallow sea	Strong local folding
SANTA MARGARITA (UPPER MIOCENE)	Granite knobs previously submerged in Monterey Sea	Like that of Vaqueros, but extending farther east	Gradual change of fauna and physical geography
MONTEREY (MIDDLE MIOCENE)	Silt, volcanic ash, Foraminifera, and diatoms	Sea without nearby land areas	Local emergence; mild vulcanism; no folding
VAQUEROS (LOWER MIOCENE)	Granite, Cretaceous sediments, and volcanic rocks	Shallow sea near rugged land	Pronounced rise of sea-level; vulcanism
EOCENE-OLIGOCENE	Same as above	Low portion of land of considerable relief	Marine transgression

of Tertiary history? In sketching a revised version of the post-Monterey disturbance it seems desirable to give, though without

all the evidence that would be desirable, enough of the Tertiary history of the region to make clear that this disturbance is only one of several, and that some of the others must have been much more violent.

VAQUEROS DEPOSITION

The limited area in which Vaqueros outcrops are found, and the abundance of coarse sandstone and conglomerate that they show, suggest that the lands of that time were rugged. In the upper part of the formation thick beds of sandy shale, with some clay shale and limestone, suggests that the period of Vaqueros deposition was closed by a marked sinking of the land, or rise of sea-level. From the evidence, now to be given, that the sea rose fairly rapidly until most of the hilltops of the Vaqueros landscape were submerged, and from the presence in Upper Vaqueros and Lower Monterey strata of thick ash beds south of the Paso Robles Basin, it appears that this disturbance, though different from that which closed the Monterey, may have been equally violent. It is the first recognizable period of diastrophic readjustment during the deposition of Tertiary strata in the Paso Robles Basin.

MONTEREY DEPOSITION

By a general submergence of the sources of clastic material it is suggested that conditions favorable for the accumulation of organic débris, such as the tests of Foraminifera and diatoms, would be inaugurated. The other factors that may have contributed to the result need not be considered here. It is more relevant to speculate a little as to the conditions that may have existed on different parts of the sea bottom. In some places, by the hypothesis, the sea must have been deeper than before by an amount equal to the total relief of the Vaqueros land areas, which were sufficiently rugged to furnish vast quantities of coarse débris to basins of limited area. The maximum depth of the Monterey Sea may thus have been anywhere from 1,000 to 5,000 feet; hardly less than the one figure, but not necessarily so much, or nearly so much, as the other. What of the submerged hilltops? Granite masses in this area are known some of which have been covered with a slight thickness of siliceous shale, apparently Upper Monterey; others, although they contributed but little detritus to the Monterey Sea, were probably

never covered with diatomite. These facts suggest that the submerged hilltops may have been continually swept clear of organic ooze by currents. The finer particles of the weathered débris may likewise have been swept into the deeps to form a part of the Monterey formation. Coarser particles, of the sand and gravel grade, were presumably left until later. A submarine process akin to weathering may even have attacked the granite and contributed to the débris.[1]

Before turning to later events it is necessary to notice one correction needed by the simplified picture of Monterey conditions just presented. The maximum thickness of Monterey shale in the Santa Lucia foothills is at least 3,000 feet; it appears to be 5,000 feet or more in Reliz Canyon. To avoid the assumption that in early Monterey time the sea was nearly a mile deep, one may assume that some parts of the sea bottom continued to sink during diatomite accumulation, but that the hypothetical hilltops, which probably belonged to separate fault blocks then as now, sank less or not at all. In the absence of exact knowledge one must choose the combination of conditions that seems to him least objectionable.

POST-MONTEREY DISTURBANCE

At the close of shale deposition, with or without an erosion interval that must have been brief where it occurred at all, there was a resumption of the deposition of coarse granitic sand (the Santa Margarita). On the hypothesis just sketched the change could have been brought about simply by a reversal of the processes that initiated the deposition of organic ooze. A rise of the sea bottom, probably even smaller than the earlier sinking, a mild recurrence of vulcanism, and the other mild events that can be deduced from the data already given in regard to the unconformity—these constitute the second period of disturbance that can be made out for the Tertiary record of the Paso Robles Basin.

SANTA MARGARITA–PONCHO RICO CONDITIONS

A striking feature of the lower portion of the sandy strata resting on the Monterey shale (Santa Margarita, in the strict sense) is the large amount of cleanly washed, white, granitic sand that it con-

[1] On the possible importance of submarine decomposition, see Arnold Heim, "Über submarine Denudation und chemische Sedimente," *Geologische Rundschau*, Vol. XV (1924), p. 6, etc.

tains. One sample proved to contain almost nothing but quartz grains, an extremely unusual condition for a Tertiary sandstone. On the hypothesis here proposed this sand came from the previously submerged, current-swept granite knobs, which had never been covered by organic sediments. The post-Monterey disturbance, in raising much of the bottom of the Monterey Sea to sea-level, had brought these knobs high enough so that they had begun to undergo vigorous erosion.

In higher parts of the series, diatomite occurs on a great scale; also clastic shale, yellowish sandstone, and conglomerate beds in which Monterey shale pebbles play an increasingly prominent rôle toward the top of the series. These are the strata here grouped together as the Poncho Rico formation.

In the Nacimiento ranch region, in Reliz Canyon, and in the Cholame hills, there are folds which seem to have been made at the close of Poncho Rico time. They involve, to the same degree, all strata older than the Paso Robles formation. This period, the first at which Tertiary strata can be shown to have been folded, constitutes the third disturbance that took place in the Salinas Valley during Tertiary time.

PASO ROBLES AND LATER HISTORY

The post–Poncho Rico sediments are considered non-marine. Some of them are clearly lacustrine; others appear to be fluviatile. It is likely that the Paso Robles Basin was occupied at different times by one or more lakes in and about the borders of which materials were deposited by streams coming mostly from the north. The matter cannot be argued here, but a great many facts suggest that the northward outlet of the Salinas River may not have existed before the close of Paso Robles deposition. The earlier northward opening of the basin was rather along the present course of the Carmel than of the Salinas River. Tentatively, then, it may be assumed that the deposition of Paso Robles strata was brought to a close by a displacement along the King City fault; and that this displacement first allowed the Salinas River to flow northward. The diastrophism that accomplished these changes may have occurred considerably earlier than the post-Pliocene folding movements of

the San Joaquin Valley. It was nevertheless the beginning of the important late Tertiary and post-Tertiary orogenic activity—the fourth disturbance since the beginning of Vaqueros deposition—that brought about many of the complicated conditions usually attributed to the post-Monterey disturbance.

SUMMARY AND CONCLUSIONS

1. Of many excellent, widely scattered exposures of the Santa Margarita–Monterey contact in the Salinas Valley, not one shows any measurable angular discordance.

2. The various kinds of indirect evidence upon which the hypothesis of an angular unconformity has been based have proved upon examination to be either incorrect or readily susceptible of a different interpretation.

3. In view of the great importance to the historical geologist of a proper interpretation of unconformities, it appears that some of the criteria ordinarily used for their recognition and evaluation are too easily misapplied to be particularly useful.

4. The available data suggest that the Neocene history of the central Coast ranges includes at least four periods of diastrophism: one each at the close of Vaqueros, Monterey, Poncho Rico, and Paso Robles time; and that the post-Monterey disturbance may have been the mildest of the four. There seems, at any rate, to be no escape from the conclusion that this disturbance, at least in its type locality, was much less violent than many geologists have believed.

THE STRUCTURAL DYNAMICS OF THE LIVERMORE REGION

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ABSTRACT

In the Coast Range 40 miles southeast of San Francisco, California, are north-northwesterly dominant faults, west-northwesterly branch faults, and northwesterly folds. Faults and folds independently prove that the axis of greatest total shortening has the bearing N. 42 E. Since Miocene times the southwestern block of the Sunol fault (dominant) has moved 12 miles northwesterly with respect to the northeastern block. Folding has occurred since the fault pattern was established. Dragged structures along dominant faults, local variations in axes of greatest total shortening, and reversed motion on branch faults in the southwest prove deformation under rotational stress by northerly and southerly forces.

In the Livermore region, a portion of the Coast Range of California which lies 40 miles southeast of San Francisco, the discovery that there were interrelationships between the folding and faulting led to the proof that the forces involved have been rotational in character.

Since 1905 the Stanford Geological Survey has spent many summers in the Pleasanton, Tesla, San Jose, and Mount Hamilton quadrangles. In this paper these quadrangles will be designated the "Livermore region." As an independent student, as instructor, and as assistant director of this survey, the author has had the opportunity of developing the structural studies of the survey.[1] The

[1] He desires to acknowledge the assistance and criticism cordially rendered by C. F. Tolman, Eliot Blackwelder, Bailey Willis, A. F. Rogers, and J. P. Smith, of the Stanford Department of Geology; B. L. Clark, of the University of California; and A. J. Tieje, of Los Angeles.

Structural studies made in connection with the water resources have been made by A. C. Lawson; and J. C. Branner, *The Future Water Supply of San Francisco*, San Francisco, 1912; W. O. Clark, "Ground-Water Resources of the Niles Cone and Adjacent Areas, California," *U.S.G.S. W-S.*, p. 345-H.

geology of the surrounding regions has been worked out by various geologists.[1]

Abreast of San Francisco Bay the Coast Range is separated into two subequal, longitudinal portions by the depression in which San Francisco Bay lies. The Livermore region lies across the easterly division. Apart from the alluvium of the Santa Clara Valley in the southwest and the San Joaquin Valley in the northeast, the region is essentially mountainous. The mountains may be divided physiographically and structurally into three blocks which trend from southeast to northwest. The middle of these, the Livermore block, is high in the southeast, low in the middle where the Livermore Valley crosses it, and moderately high in the northwest. Between the Livermore block and the Santa Clara Valley is the Mission Ridge block. These blocks are separated by the Sunol fault. To the northeast the Altamont hills block lies between the Livermore block and the San Joaquin Valley. In the north these blocks are separated by the Riggs Canyon fault, but in the south they blend together.

THE FAULT SYSTEM

THE DOMINANT FAULTS

The prominent structural feature of the region is a group of four faults which are more or less similar in direction and characteristics to the San Andreas fault, which traverses the quadrangles to the west of the Livermore region. These will be called the "dominant faults." From southwest to northeast they are the Haywards, Sunol, Riggs Canyon, and Midway faults (Fig. 1).

THE SUNOL FAULT

The Sunol fault is the most satisfactorily exposed of the group. It is known as far north as Napa County, trends southeasterly across the Contra Costa County hills and the Livermore region, and joins the San Andreas fault near Tres Pinos 42 miles south of the

[1] J. C. Branner, J. F. Newsom, and Ralph Arnold, "The Santa Cruz Folio," *U.S.G.S. Folio 163.*

A. C. Lawson, "The San Francisco Folio," *ibid., Folio 193.*

B. L. Clark, "The Mount Diablo Region," oral communication.

R. Anderson and R. W. Pack, "Geology and Oil Resources of the West Border of the San Joaquin Valley, North of Coalinga," *U.S.G.S. Bull. 603.*

Stanford Geological Survey, *The Morgan Hill Region* (unpublished).

Livermore region. As a result of brecciation and alluviation, the fault plane is seldom exposed (exception: Calaveras Dam). The trace

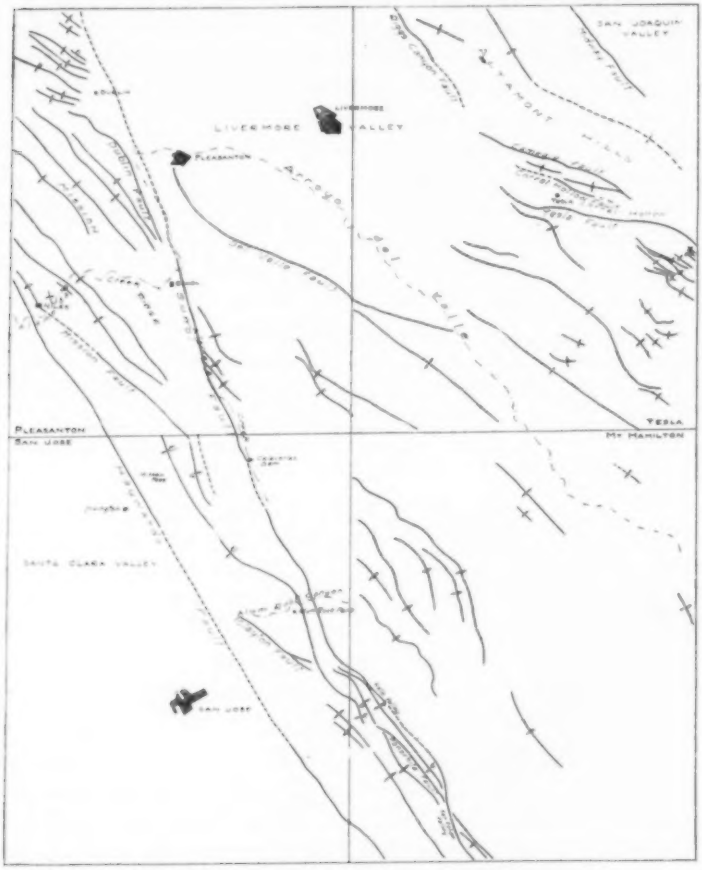

FIG. 1.—Showing the fault and fold patterns of the Livermore region

of the fault, even in mountainous regions, is remarkably straight. This fact has led to the conclusion that the zone is essentially vertical. The old topographic surface[1] frequently has been warped

[1] In early Pleistocene time a topographic surface—in part senile, in part mature—was formed in the Livermore region. It will be termed an "old surface." After rejuvenation the surface has been dissected by erosion.

downward toward the Sunol fault, sometimes to such an extent that alluvium has accumulated along the fault line. The western end of the Livermore Valley is terminated by a scarp that has been formed by the uplift of the Mission Ridge block along the Sunol fault. In various places the course of the fault is marked by consequent or subsequent streams. The trend of the fault is N. 25° W.

Structure, stratigraphy, and physiography show that blocks on opposite sides of the Sunol fault have had different histories. At a point on the Sunol fault 4 miles south of Sunol, the eastern block is composed of Miocene strata that rest on a complex Jurassic basement. The western block reveals a somewhat different phase of Miocene strata that rest on Cretaceous formations. At an equal distance north of Sunol the easterly block is composed of late Pliocene land beds which are covered by alluvium. Cretaceous strata alone compose the block to the west.

In topography there is a marked difference on opposite sides of the Sunol fault. From the southerly to the northerly points mentioned, the land surface of the eastern block passes from a recently rejuvenated area, that was formerly in its late maturity, to an alluvial fill. On the west the old physiographic surface has been upwarped into an arch whose axis, which parallels the Sunol fault, attains an elevation of 2,000 feet in the north and the south, but at an intermediate point, Mission Pass, reaches an altitude in the saddle of only 800 feet.

Professor C. F. Tolman has found that the direction of the vertical component of motion on the Sunol fault has changed. Where Alameda Creek follows the fault rift, the easterly block was elevated above the westerly between the Cretaceous and the Lower Miocene periods, and its Cretaceous sediments removed by erosion. After Lower Miocene time, sediments were deposited on both blocks. After this, uplift on the westerly block raised these sediments to a position structurally above their position on the easterly block.

The conception that the motion on the San Andreas type of faults is predominantly horizontal was established when the disturbances along the San Andreas fault were analyzed after the San Francisco earthquake in 1906.[1] At this time movement of the south-

[1] A. C. Lawson and associates, *Report of the California State Earthquake Investigation Commission* (Carnegie Institution of Washington), Pub. 87, Vol. I (1908), Part I, p. 53.

west block was northwesterly with respect to the northeast block. On the Sunol fault the relative unimportance of the vertical motion may be shown by a study of the Pleistocene topographic surface on opposite sides of the fault. In spite of the fact that the old surface may be uplifted and arched to various elevations a mile or so from the fault rift, the surface is frequently, if not generally, so warped that it stands approximately at the same level on opposite sides of the fault line. The most marked exception to this generalization is the locality where the Livermore Valley is truncated by the Sunol fault.

Near Calaveras Dam portions of the footwalls of several faults in the Sunol Zone have been exposed in a hydraulic excavation. The strike is almost due north, and the westerly dip varies from 31° to 53°. The motion has been almost parallel to the strike, but varied in a few places to N. 38 E. The hanging or northwesterly wall has moved northerly and northeasterly with respect to the foot wall. This is shown by the ramplike masses of gouge that lead up to the polished surfaces on the southerly faces of the pebbles set in the foot wall, and by the plucked surfaces on the northerly faces, as well as by the concentric zones of crushed gouge in the foot wall directly north of the pebbles.

The strike shift of the structural and stratigraphic units shows the direction and amount of movement on the Sunol fault. The Briones formation is a series of sandstones and shell-breccia beds whose phases may easily be recognized. It overlies the Temblor formation, which likewise has distinctive phases. On the westerly side of the Sunol fault northwest of Dublin, the Briones formation is characterized by shell-breccia reefs, and the Temblor is a sandstone. A similar series lies on the easterly side of the fault southeast of Sunol. In fact, the two areas are so alike that *Astrodapsis brewerianus* (Remond) is found only in the northeasterly portion of each. Measuring between corresponding points, namely, the southerly intersection of the Briones contact with the fault, the strike shift is 12 miles. Between two Lower Miocene localities characterized by the abundance of *Pecten propatulus* Conrad the measurement is 13 miles, and between two (the only two) Pliocene rhyolitic local-

ities, it is 9 miles. Similarly, near Alum Rock Park sandy Briones beds which rest on Temblor opalized shale on the westerly side of the Sunol fault correspond to a similar series south of the San Felipe Valley. The strike shift is again 12 miles. A slight portion of the apparent displacement is due to the gentle pitch of the structures, but since the folds are truncated by the fault in each case, the factor cannot be considered causal.

THE HAYWARDS FAULT

Throughout most of its length in the Livermore region, the Haywards fault is masked by the alluvium of the Santa Clara Valley. It has been recognized by R. E. Dickerson[1] 55 miles north of the Livermore region on Sonoma Mountain near Petaluma. Dr. A. C. Lawson has discussed it in connection with the Berkeley hills,[2] and as the cause of the San Francisco earthquake in 1868.[3] Northwest of Niles, where the Haywards fault traverses low hills, it produces a complicated fault zone. Across the Niles alluvial cone it can be traced by its effect on the underground water. Near Irvington it forms a scarp. Eight miles south of the area it unites with the Sunol fault east of Morgan Hill. The trend of the Haywards fault is N. 33 W.

THE RIGGS CANYON FAULT

The Riggs Canyon fault traverses the westerly margin of the Altamont hills. It can be traced as a contact along which minor faulting occurs in a southeasterly direction from the Mount Diablo region, where it was recognized by Dr. B. L. Clark,[4] to a point near the western terminus of Altamont Pass, and, physiographically, 3 miles farther. Although short, it has the straightness, direction, and some of the structural and physiographic characteristics of the dominant faults. Its trend is N. 37 W.

[1] "Tertiary and Quaternary History of the Petaluma, Point Reyes, and Santa Rosa Quadrangles," *Calif. Acad. Sci. Proc.* (4th ser.), Vol. XI, No. 19. San Francisco, 1922.

[2] A. C. Lawson and C. Palache, "The Berkeley Hills," *Univ. Calif. Pub. Dept. Geol.*, Vol. II, No. 12. Berkeley, 1902.

[3] A. C. Lawson, "The Mobility of the Coast Ranges of California," *ibid.*, Vol. XII, No. 7. Berkeley, 1921.

[4] Oral communication.

THE MIDWAY FAULT

A small fault, scarcely more than a fracture, lies to the east of Midway. The trend, N. 41 W., requires that it should be mentioned among the dominant faults.

THE BRANCH FAULTS—THE TESLA TYPE

Closely associated with the dominant faults is a series of faults that branch from those of the San Andreas type. The Del Valle, Panochita, Dublin, Bolinger,[1] and Las Trampas[1] are associated with the Sunol fault, and the Tesla, Corral Hollow, and Carnegie with the Riggs Canyon fault, and the Clayton and Mission Peak with the Haywards fault.[2] These faults characteristically trend west-northwest to east-southeast. They may occur on either side of the dominant faults. Although they are prominent near the dominant faults, away from them, the branch faults frequently blend into other structures and disappear.

THE TESLA FAULT

One of the branch faults, the Tesla, lies a mile south of Corral Hollow. It is a typical branch fault. Its strike is N. 72 W., and its hade, although almost vertical, varies in direction from side to side along the trace of the fault. To the north, Cretaceous and Tertiary formations whose strikes almost parallel that of the fault, are ultimately truncated by the fault, whereas to the south, Jurassic folds trend into it. The closely folded strata in Corral Hollow attest to the compression exerted from block to block through the fault plane. Vertical fault striae east of the area and the greater age of the strata on the south show that the southern block has been elevated with respect to the northern. To the southeast the fault blends into a monoclinal structure, and to the northwest disappears at the border of the alluvium of the Livermore Valley. Throughout most of the length of the fault the surface of the Jurassic rocks on the south is higher than that of the later rocks on the north. This may be attributed to uplift of the southern side, or to erosion of the softer rocks on the northern side.

[1] "Concord Sheet, San Francisco Folio," *U.S.G.S. Folio 193.*

[2] The Vergeles fault of the San Juan Bautista quadrangle, the Black Mountain of the Santa Cruz quadrangle (*U.S.G.S. Folio 163*), and the Pilarcitos and San Bruno of the "San Mateo Sheet of the San Francisco Folio" (*U.S.G.S. Folio 193*) are similarly connected with the San Andreas fault.

MINOR DIP FAULTS

There are numerous normal faults of minor importance that trend in a northeasterly direction, perpendicular to the axes of folding. These are prominent where reef beds are included in the sediments, as, for instance, northwest of Dublin and southeast of Sunol. Petty adjustments incident to folding have taken place along these faults.

ABSENCE OF CERTAIN TYPES OF FAULTS

One of the interesting features of the area is the absence of major faults whose trend is northeasterly. In the surrounding regions they are rare.

THE FOLDS

In regard to folding the Livermore region may be divided into districts, each of which displays relatively uniform characteristics. The one similarity between the various districts, the trend of the axes of folding, is closely connected with the fault pattern.

FOLDING IN THE LIVERMORE BLOCK

The Livermore Valley is a synclinal depression. The northern flank may be considered as a monocline, or possibly an isocline, which extends northwesterly into the Mount Diablo quadrangle.

On the southern flank the younger strata, which form the margin of the valley, are separated from the Jurassic area to the south in part by erosional and in part by fault contacts. Along the Arroyo del Valle the Cretaceous strata strike N. 50 W. These and the Jurassic strata have been arched into a faulted anticline which pitches northwesterly toward the southwest portion of the Livermore Valley. Miocene and later strata have been deposited unconformably on this structure, and have been deformed so that they swing around the nose of the anticline toward the Sunol fault. East of Arroyo del Valle the beds dip monoclinally to the northeast.

South of these structures and also south of the corresponding structure in Corral Hollow lies an extensive exposure of the Jurassic rocks which form the core of the Coast Range. The strata have been folded into broad synclines and crushed anticlines. Its complexity results from minor folding, faulting, intrusion, and metamorphism. The trend of the axes of folding varies from N. 46 W. to N. 55 W.

Between the Jurassic area and the Sunol fault, 3 miles southeast of Sunol, is a series of folded Miocene and Lower Pliocene strata. Although the folds near the Jurassic border are open, those near the Sunol fault are closely compressed. The trend of the axes varies from 40° to 50° west of north.

FOLDING IN THE MISSION RIDGE BLOCK

North of the Dublin fault is another area of Miocene and Lower Pliocene strata which is similar to that southeast of Sunol. The folds are closely compressed, and in the major syncline Pliocene strata are overturned so that both flanks dip northeasterly. The trend is N. 60 W.

Between Dublin and Sunol, Cretaceous strata are folded into closely compressed anticlines and synclines. Between Sunol and San Felipe Valley, Tertiary beds are folded with the Cretaceous strata. Shell breccia reefs of Miocene age dominate the superficial structures. A syncline near Alum Rock Canyon is overturned in a manner similar to that of the northern one. South of San Felipe Valley, Lower Cretaceous strata are exposed. The trends of the axes of folding are approximately N. 45 W.

THE ALTAMONT HILLS BLOCK

In marked contrast to the closely folded structures found elsewhere in the region the area east of the Riggs Canyon fault and north of the Carnegie fault is characterized by open folds. Cretaceous, Upper Miocene, and Lower Pliocene strata are involved. The trend of axes is northwesterly.

Crushed between this block on the north and the Jurassic mass on the south, there is in Corral Hollow a folded and faulted zone of strata that range from Lower Cretaceous to Pliocene in age. The strata on the northern flank of the zone resemble those on the northern flank of the Livermore syncline, whereas on the southern flank the resemblance is to those on the south side of the Livermore Valley. The dominant strike is N. 70 W. The change from the open structure of the Livermore syncline to the crushed zone of Corral Hollow takes place at the southern termination of the Riggs Canyon fault.

THE EXPERIMENTAL WORK OF W. J. MEAD

In his experimental work W. J. Mead[1] has produced under rotational stress fault and fold patterns that are remarkably similar to those in the Livermore region (Fig. 2).

FIG. 2.—Folds in plaster of Paris produced by shearing deformation. (After experiments performed by W. J. Mead.) The relationship of the applied forces and the folds is the same as that found in the Livermore region. Professor Mead printed his photographs "left for right" to make conditions correspond to those found by the author.

AGE OF THE FAULTS AND FOLDS

On the assumption that major fault lines are more apt to originate in periods of diastrophism than in those of quiet, it can be shown that the Sunol fault dates from or before the epi-Jurassic interval. Although Franciscan (Jurassic?) and Lower Miocene strata are present on both sides of the fault along Alameda Creek, the Cretaceous series, which is well developed on the western side of the fault, is absent on the eastern side. Since the Cretaceous series is known in many localities in and around the Livermore region, and has the characteristics of a widespread deposit, the discordance cannot be explained by local deposition. Movement and differential erosion, therefore, must have occurred before Lower Miocene time.[2] Similar evidence is found on the Del Valle fault, and suggestive but less conclusive evidence on many other faults.

[1] "Notes on the Mechanics of Geologic Structures," *Jour. Geol.*, Vol. XXVIII, p. 505. Note that in a comparison Figs. 5 and 12 must be turned left for right. The tension fractures under the experimental conditions are necessarily exaggerated.

[2] Explorations to the north and the south have produced no evidence which shows that the horizontal movement along the Sunol fault is sufficient to account for the juxtaposition of two such different sequences.

The unconformity between the complex Franciscan rocks and the overlying Cretaceous beds suggests that some of the folding in the Franciscan series occurred in the epi-Jurassic interval. However, as closely folded structures include Lower Pliocene beds and are overlaid by early Pleistocene beds, much of the folding must have occurred toward the end of the Pliocene period.

STRUCTURAL INTERRELATIONSHIPS

If it be assumed that the earth's crust drifts on the underlying rock, the dominant and branch faults may be considered as fractures formed in a solid body when under compression its ultimate strength is exceeded. If the method of employing the strain ellipsoid, which is ordinarily used to determine the direction of movement between strata, be applied to the Livermore region, the theoretical conclusion is reached that the movement of the block on the southwest side of a dominant fault must be northwesterly with respect to that to the northeast. This type of motion occurred on the San Andreas fault in 1906.[1] It has been proved for the Sunol fault by details on the fault plane and by the displacement of stratigraphic units.

If, as has been found in mechanics, a substance be compressed beyond its ultimate strength, in case of non-rotational strain, fractures will be formed at approximately 45° to the direction of the compressive force. In other words, the axis of the compressive force bisects one of the angles between the sets of conjugate fractures. In nature, compressive forces are seldom directly opposed, but are applied as couples, and are termed "rotational." When rotation occurs, although the axis of greatest (total) shortening bisects the angle between the fractures, the axis of the compressive force lies between the axis of greatest (total) shortening and the dominant fracture. A rotational strain may be resolved into a non-rotational strain and pure rotation. In the following discussion the system of fractures and folds will tentatively be considered as non-rotational. Later the evidences of rotation will be presented.

[1] A. C. Lawson and associates, *loc. cit.*

STRUCTURE WITH REFERENCE TO THE AXIS OF GREATEST TOTAL SHORTENING

THE AXIS OF GREATEST (TOTAL) SHORTENING AS DEDUCED FROM THE FOLDING

The axis of the greatest (total) shortening may be deduced from the folding. In the Livermore region the axes of folding, with the exception of a few folds and segments of folds that lie in fault zones, trend in directions that lie between N. 37 W. and N. 70 W. Those that approach the former value are in the southwest, and those that approach the latter are in the northeast. The average trend for the whole area is N. 49 W. The axis of greatest (total) shortening has the bearing N. 41 E.

THE AXIS OF GREATEST (TOTAL) SHORTENING DEDUCED FROM THE FAULT PATTERN

The average bearing of the dominant faults in the Livermore region is N. 34 W., and that of the branch faults is N. 61 W. The folding establishes the quadrant in which the axis of greatest (total) shortening lies. The bisectrix of the appropriate angle has the bearing N. 43 E.

EFFECT OF FOLDING ON THE ANGLE BETWEEN FRACTURES

The bisectrix divides the obtuse angle. The axes of folding are perpendicular to the bisectrix, and, when prolonged, intersect the dominant and branch faults. No matter what the initial angle between the faults may have been, subsequent folding will open the angle in which the axis of greatest (total) shortening lies, because the various segments of folds approach the apex without significant loss of length. This is shown in Figure 5*a*.

THE AXIS OF GREATEST (TOTAL) SHORTENING AS INDICATED BY OVERTHRUSTING

Although only minor overthrusts occur in the Livermore region, important faults of this character are found not far beyond its limits. One of these lies in the Santa Cruz Mountains southwest of San Francisco Bay. Three thrust faults arranged *en echelon* correspond to the ridges: Ben Lomond, Butano, and an unnamed ridge south of San Gregorio Creek. Movement on these faults was

toward the northeast. On the opposite side of the Livermore region near Mount Diablo, Dr. B. L. Clark[1] found complicated thrusting in which the hanging wall moved southwesterly with respect to the foot wall.

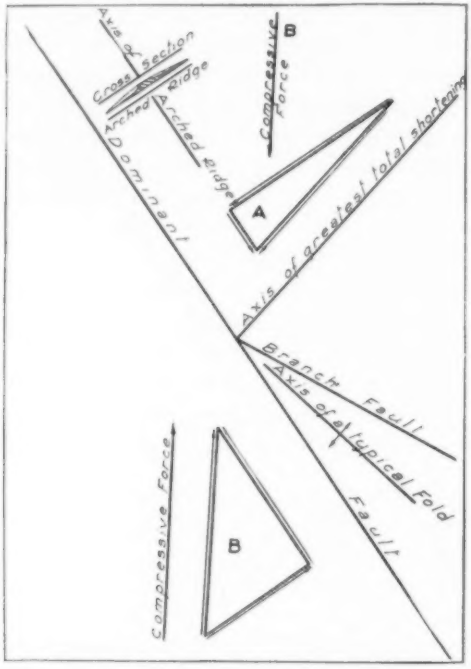

FIG. 3.—Resolution of forces with respect to the dominant fault: *A*, when the compressive force is assumed to be parallel to the axis of greatest (total) shortening; *B*, when the compressive force acts as a couple.

MOVEMENT ON FAULT PLANES

Utilizing N. 42 E., the average value of the direction of the axis of greatest (total) shortening, as that of the greatest stress, and N. 34 W. and N. 61 W. as the average trends of the dominant and branch faults, respectively, the resolution of forces (Fig. 3*a*) shows the component of motion parallel to the fault plane. It is apparent that if

[1] Oral communication.

motion occurs on a dominant fault, the southwest block will move northwesterly with respect to the northeast block, whereas, if motion takes place on a branch fault,[1] the southwest block will move southeasterly with respect to the northeastern block. Motion on faults of one type will hinder motion on those of the other type, because movement on one fault places a fault block in the path of the other. This interference results in the differentiation of major faults in two groups: those on which motion may take place freely and those on which it is hampered. Structure, physiography, and seismology indicate that the dominant faults belong to the former group, whereas the characteristics of the branch faults place them in the latter.

THE COMPONENT PERPENDICULAR TO THE DOMINANT FAULTS

In Figure 3*a* it is apparent that the component which acts parallel to the fault is much less than that normal to the fault. A strike slip of 12 miles on the Sunol fault since Miocene time, and unknown displacements on the Haywards and Riggs Canyon faults suggest great movement, normal to the dominant faults. The amount of movement depends on the absorption of energy by friction, etc. If gliding motion is possible on the fault planes, and compression of the rock is difficult, the relative movement normal to the fault will be slight. Under these conditions the force imparted to the block beyond a fault would produce folds parallel to the fault. This is not the case in the Livermore region.

In the Livermore and Santa Cruz regions there are long ridges that parallel the dominant faults. The Pleistocene land surface has been warped into an arch in the formation of these ridges. They have since been modified by erosion. The warping can be explained by the compression of the rocks beneath by forces normal to the axes of the arches. In the Santa Cruz region the Cahill–Castle Rock and the Montebello-Pulgas ridges are parallel to the San Andreas fault.[2] In the Livermore region, Mission Ridge parallels the Sunol fault, and the Altamont hills the Riggs Canyon fault. Anticlines and synclines cross these arched ridges diagonally. The absence of

[1] Note exception discussed in the case of rotational stress.

[2] F. P. Vickery, *The Physiography of the Santa Cruz Quadrangle* (manuscript). Stanford University, 1919.

marked domes at the intersection of the arched ridges and the anticlines shows that this type of deformation is not an important factor. The shortening since Pleistocene time in the Livermore region is about 1,000 feet.

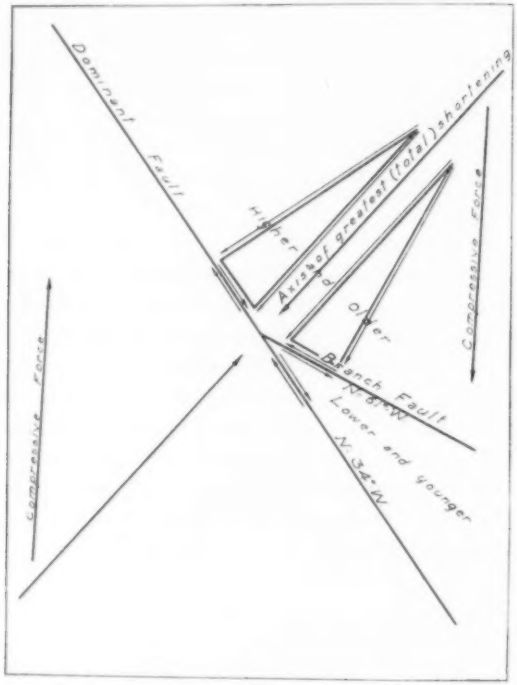

FIG. 4.—Resolution of forces showing components that produce relative elevation of the obtuse-angle and depression of the acute-angle blocks. Based on the assumption that the faults are vertical.

DIFFERENCES IN ELEVATION AND AGE IN THE OBTUSE- AND ACUTE-ANGLE BLOCKS

In an area where the rocks are poorly cemented, fractured, and folded, it is reasonable to anticipate that where the pressure is abnormally great the blocks will be locally thickened. As is shown in Figure 4, the motion of the masses in the obtuse-angle blocks will

be toward the apices, whereas that in the acute-angle blocks will be away from these points.[1] If the values of the hade are slight, this crushing raises the surface of the obtuse-angle blocks, and, in course of erosion cycles, will result in the exposure of older rocks than are found in the acute-angle blocks. Physiographically, this is the case where the Panochita, Dublin, Bolinger, Las Trampas, and Del Valle faults meet the Sunol fault, and where the Clayton and Mission faults join the Haywards fault.[2]

From the standpoint of exposure of older rocks in the obtuse angles, the theory is confirmed in the cases where the Panochita, Dublin, Bolinger, and Las Trampas faults meet the Sunol fault,[3] and where the Clayton and Mission faults join the Haywards fault.[4]

TRANSMISSION OF ENERGY FROM THE SOUTHWEST TO THE NORTHEAST

The southwestern portion of the area is characterized by active faults, close and sometimes overturned folds, and an obtuse angle of 152° between the dominant and branch faults. In contrast to these characteristics the extreme northeastern part of the region has less active faults, open folds, and 147° as the angle between dominant and branch faults. The angular relationship is shown in Figure 5*b*. These lines of evidence indicate that deformation has been more intense in the southwest than in the northeast, and that the energy is being transmitted from the former to the latter region.

[1] In the case of rotational strain the difference in the values of the components parallel to the dominant and to the branch faults will cause a similar result, although the mechanics are modified.

[2] Along the San Andreas fault acute-angle blocks are depressed with respect to obtuse-angle blocks in the cases of the San Mateo Creek, Pilarcitos and Vergeles faults, is obscure in that of the San Bruno (out to sea), and is possibly contrary to theory in that of the Black Mountain fault, the only questionable case.

[3] The most prominent exception to this generalization is mapped in the Concord quadrangle where the Franklin and Sunol faults meet. The evidence is obscure where the Del Valle meets the Sunol fault, because the Livermore gravels lie on each side of the branch fault.

[4] On the San Andreas fault the older rocks are exposed in the obtuse angles in the cases of the Pilarcitos and Vergeles faults. The conditions are obscure in those of San Mateo Creek and Black Mountain, because the Franciscan formation occurs on each side of the branch fault.

THE EVIDENCES OF ROTATIONAL STRESS

DRAGGING OF STRUCTURES ALONG THE DOMINANT FAULTS

The dragging or rotation of structures near the dominant faults is exemplified by the warping of the monocline north of the Liver-

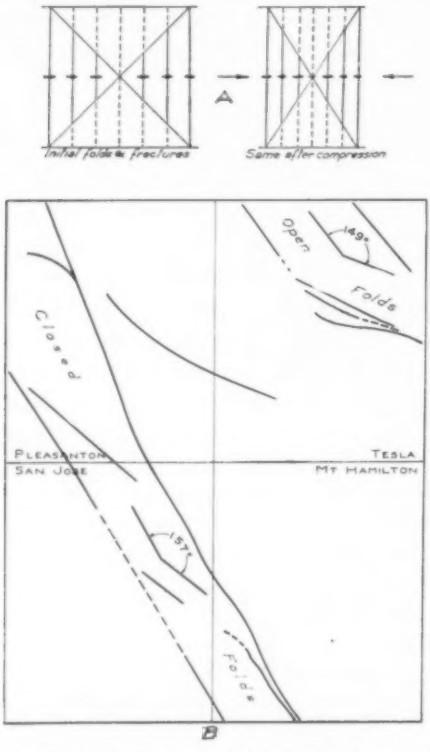

FIG. 5.—*A*, Showing the development of obtuse angles between fractures during the progress of folding. *B*, Showing the more obtuse angle in the southwest and the less obtuse in the northeast. Note the greater rotation in the southwest.

more Valley. This structure extends from the Sunol to the Riggs Canyon fault. North of the central portion of the valley the strike is N. 69 W. At the western end the strata swing northwesterly until they almost parallel the Sunol fault, and to the east they

bend southeasterly until they approach the trend of the Riggs Canyon fault.

DEFORMATION OF THE ACUTE-ANGLE BLOCKS

Under compression, as is shown in Figure 6, there is a tendency to force the acute-angle blocks away from the apices at the intersection of the dominant and branch faults. When, however, there is motion on the dominant faults, friction drags out the apical portion

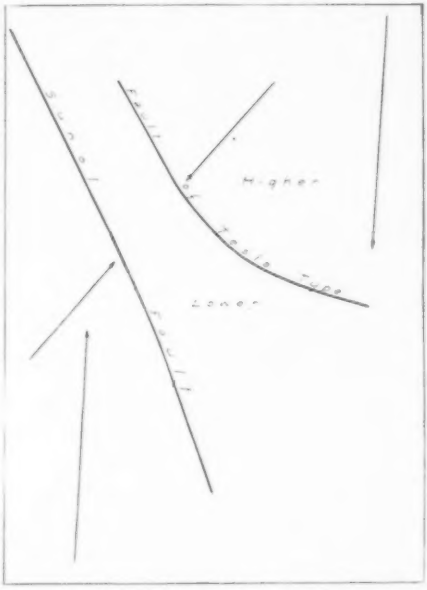

FIG. 6.—Diagram showing the dragged pattern of the acute-angle block.

of the acute-angle blocks. This deformation is increased by the rotation of the rock masses in the obtuse-angle blocks, and by movement on the dragged portion of branch faults similar to that on the dominant faults. Examples of the attenuation of acute-angle blocks occur where the Panochita, Dublin, Las Trampas, and Del Valle faults meet the Sunol fault.[1] This process and the relative depression

[1] On the San Andreas fault attenuation is shown in the cases of the Pilarcitos and Vergeles faults.

of the acute-angle blocks result in a fault pattern which is characteristic of the San Andreas and the Sunol fault zones, and lead to their interpretation as grabens or rifts.

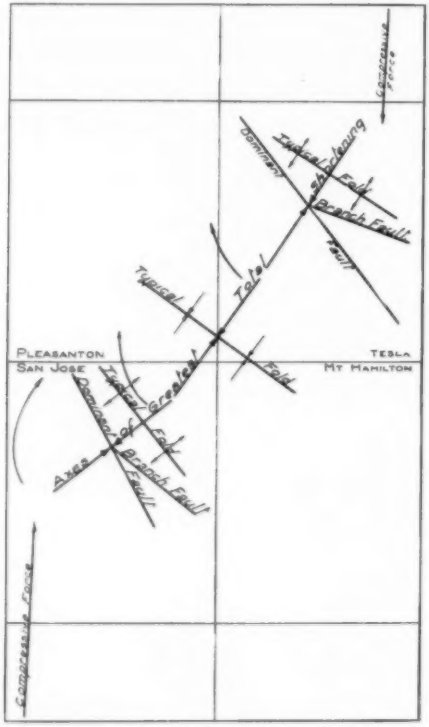

FIG. 7.—Showing a great rotation of the axis of greatest (total) shortening, in the southwest and less in the northeast.

DIFFERENCES IN THE BEARINGS OF THE AXES OF GREATEST (TOTAL) SHORTENING IN THE SOUTHWEST AND THE NORTHEAST

There is a difference in the bearings of the axes of greatest (total) shortening in the southwest and in the northeast. This is shown in Figure 7. The dominant faults in the southwestern portion of the area have an average bearing, N. 29 W., and those in the northeast

have N. 39 W. In the former region the branch faults trend N. 52 W., and in the latter N. 70 W. As determined from the fault pattern the axis of greatest (total) shortening in the southwest has as its bearing the direction N. 51 E., and that in the northeast N. 35 E.

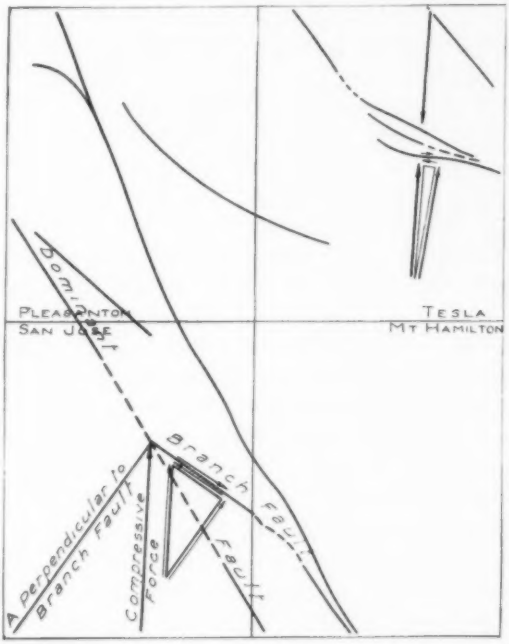

FIG. 8.—Under conditions of rotational strain a resolution of forces with respect to a branch fault shows a component which will cause a northwesterly movement of the southwest block with respect to the northeast block. This is the type of movement shown by the exposure at the mouth of Alum Rock Canyon. The component is great in the southwest and slight in the northeast.

As determined from the folding the corresponding values are N. 52 E. and N. 33 E.

If the strains had been non-rotational, the axes of greatest (total) shortening should be parallel. In the southwest where deformation is more extensive the axis of greatest (total) compression has rotated in a clockwise direction to a greater degree than has that in

the northeast. The direction of rotation is that which should be anticipated from the movement on the dominant faults.

REVERSED MOTION ON THE BRANCH FAULTS IN THE SOUTHWEST

The opening out of the obtuse angles in the southwestern part of the area to 152° reduces the acute angles to 28°. If the strain is non-rotational, the compressive force will have the bearing of the axis of greatest (total) shortening, N. 51 E., and on the branch faults the movement of the southwest block will be southeasterly with respect to the northeast block. If the compressive forces be applied as a couple, the strains will be rotational, and the compressive force, as shown in Figure 8, will be applied in a direction intermediate between N. 51 E. and the bearing of the dominant fault, N. 19 W. If the compressive force be applied in a direction closely approaching that of the dominant fault, the motion on the branch fault will be reversed.

This is the case on the southwestern margin of Mission Ridge. At the mouth of Alum Rock Canyon the plane of a branch fault is exposed. Striae and offset pebbles unite in proving that the southwest block moved northwesterly with respect to the northeast block (Fig. 8).

THE DIRECTION OF THE COMPRESSIVE FORCE

The compressive force must have been applied along a line whose direction is intermediate between that of the axis of greatest (total) compression and the trend of the dominant fault.[1] This direction is essentially northerly. The compressive force transmitted from the south was opposed by a resistant force in the north.

[1] Motion of this type is characteristic in the southwestern portion of the area, is probable in the central, but is unlikely in the northeast. Beyond the eastern limits of the area vertical motion has been noted on the Tesla fault.

EVIDENCE OF LIQUID IMMISCIBILITY IN A SILICATE MAGMA, AGATE POINT, ONTARIO[1]

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Ottawa, Ontario

ABSTRACT

As a contribution to the study of magmatic differentiation, the author reports a discovery of quartz porphyry outcrops on the north shore of Lake Superior in which there are abundant globules of glass in a main mass consisting chiefly of glass. Evidence is submitted indicating that the globules were liquid at the time the surrounding rock was liquid, and that the two parts were of different composition. In all respects, the field occurrence corresponds to the description of the hypothetical case described by Bowen as being the only kind of phenomenon which would supply indisputable proof of the existence of immiscibility in silicate magmas. The unavoidable conclusion is reached that, if Bowen's criterion is correct, the occurrence of limited liquid miscibility in silicate magmas is a fact.

Near Agate Point, on the north shore of Lake Superior, 30 miles south of Nipigon village, there is an occurrence in glassy and partly glassy extrusive lava of distinct globules of material still partly glass, and of composition different from that of the main mass.

It has been stated by N. L. Bowen[2] that an occurrence such as is here reported would establish the fact of liquid immiscibility in silicate magmas, and moreover that an occurrence of this nature is the only kind of phenomenon which could be accepted as definite proof. The discovery and recognition of this occurrence is consequently to be regarded as of momentous significance, since it is the first instance on record which satisfactorily testifies to the operation of a process in rock differentiation which has been a subject of controversy among students of petrogenesis for many years. Accepting Bowen's apparently sound criteria for its recognition, liquid immiscibility in silicate magmas may now be accepted as an established fact.

It does not come within the scope of this article to discuss fully the extensive literature dealing with the subject of liquation or the

[1] Published with the permission of the Director, Geological Survey of Canada.

[2] "Later Stages of Evolution of Igneous Rocks," *Journal of Geology, Supplement* to Vol. XXIII, No. 8 (1915), p. 10. The statement here referred to is confirmed, and thus brought up to date, in a personal communication from Dr. Bowen, received February, 1925.

separation of non-consolute fractions in silicate magmas; it is sufficient to state that for many years there have been students of petrogenesis who believed that the process has been operative in differentiation, or in bringing about the formation of rocks of different composition from a single magma. In recent years, however, the results of detailed experiments with uncontaminated synthetic magma material have accumulated; and, largely as a result of the excellent publications by Vogt[1] and Bowen,[2] it has come to be known that liquation does not occur under the various conditions investigated. These authorities agree in believing all silicate melts formed in nature to be consolute, and do not accept as evidence of liquation those phenomena which had been thus interpreted.

The writer has failed to find a description in previously published literature of an occurrence which could be positively identified as corresponding to the hypothetical case described by Bowen as the only kind of phenomenon which would furnish indisputable proof of immiscibility in silicate magmas. There are, however, several descriptions of color-banded quartz porphyry such as that which occurs near Agate Point, and it is probable that the globule-bearing phase of that locality is not unique.

Agate Point, latitude 48° 35′ 24″, longitude 88° 11′ 45″, forms the termination of a peninsula ½ mile wide at the base, which projects southerly 1 mile into Lake Superior from a shore line which for several miles trends approximately northeast and southwest.[3]

It is situated within a crescent-shaped area, underlain by Keweenawan lavas, associated pyroclastics, and later diabasic intrusives. The lava series is very thick[4] and is composed of a great number of flows. Amygdaloidal basaltic flows preponderate; a quartz porphyry flow, remnants of which occupy considerable areas on the southerly or lakeward side of the crescent for 21 miles east of Agate Point, and the sill of similar composition farther east on Simpson Island represent but a small percentage of the total volume. The quartz porphyry occurs stratigraphically near the top of the lava series.

[1] J. H. L. Vogt, "Silikatschmelzlösungen," *Vidensk. Selsk Skr.*, No. 1, 1904, etc.

[2] N. L. Bowen, *Journal of Geology*, Vol. XXVII, No. 6 (1919).

[3] Canadian Hydrographic Survey Chart 102.

[4] Six thousand to 10,000 feet estimated by W. E. Logan, *Geology of Canada* (1863), p. 71.

The peninsula of which Agate Point is the termination is composed of quartz porphyry and related rocks and a few small diabase dykes of later age. The quartz porphyry near the base of the peninsula and for $\frac{1}{4}$ mile north of the point is a lava, and it is similar to the quartz porphyry found over a wide area to the northeast; it is com-

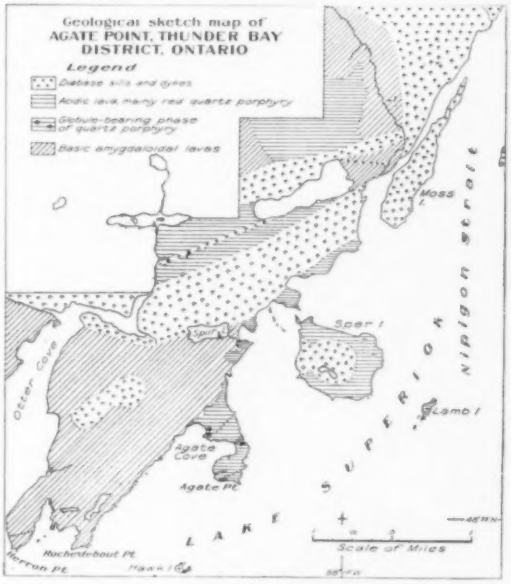

FIG. 1.—Geological sketch map showing the distribution of globule-bearing quartz porphyry, Agate Point, Ontario.

paratively homogeneous, red, dense, hard, massive, and fresh-looking, with sparsely scattered amygdules filled with white agate, quartz, and calcite.

In the central part of the peninsula there is a remarkable assemblage of quartz porphyries and obsidian showing a wide range of beautiful colors, a variety of textures and internal structures, and striking flowage phenomena. Within this area there are three outcrops showing an abundant development of globules, as indicated in Figure 1.

On the east shore of the peninsula ½ mile north of Agate Point in an indentation called Glory Bay, there is a small cave, eroded in a vertical, platy mass of soft, earthy, red-and-green-mottled, hydrothermally altered quartz porphyry. Through the central part of this mass there are several vertical veinlets of purple fluorite. On either side of this soft material the rock is hard, dense, fresh-looking, red quartz porphyry (Fig. 2) through which simple and compound globules of quartz porphyry from ½ inch to 1 inch in diameter and of different colors are rather evenly distributed in polka-dot fashion. The material of this character stands as nearly vertical layers 30 feet high and approximately 15 feet wide.

FIG. 2.—Photograph of outcrop of globule-bearing quartz porphyry, Glory Bay, Agate Point.

The outcrop, which is almost continuous for 250 feet to the north of the globule occurrence, is of remarkable beauty, and the rocks are of a great variety of colors arranged in various patterns. There is an imperfect platy jointing in these rocks which accords with the flowage lines where these are present (Fig. 3); this structure stands vertically in the low southern part near the pale-red-and-green, soft rock. In the upper part of the outcrop and in the adjacent rock to the north it curves gently over toward the north, and this curving continues so

that within 100 feet the structure is approximately horizontal. Farther north the structure, where visible, is curved in an intricate, swirled manner.

Proceeding northerly across the outcrop in the over-curving structure, a transitional change is to be observed in the internal structure (Fig. 4). The polka-dot distribution of the globules becomes compressed, the number of composite globules increases, and where several of these have joined they form tuberous masses; the

FIG. 3.—Photograph showing jointing and flow structure in quartz porphyry, Agate Point.

spherical shape of the globules changes to drawn-out ellipsoids, and within a comparatively short distance they give place to broad, thin plates in parallel orientation. The quartz porphyry here presents a banded appearance; the bands of different colors are sharply defined, and the platy structure curves broadly with numerous minor plications and swirls in an intricate flowage pattern. Certain bands (in study specimens these are 2 millimeters or more in width) are bounded on either side by a film of different color from the rock on either side of it; other bands which may be identical in every other respect lack these bounding films. The width of the bands becomes progressively thinner and less sharply defined until a phase is reached

where the bands, though quite distinct, are of paper thinness and the color contrast between the disseminated red feldspar phenocrysts and the violet-gray matrix is more striking than that between the thin, differently colored bands of glass.

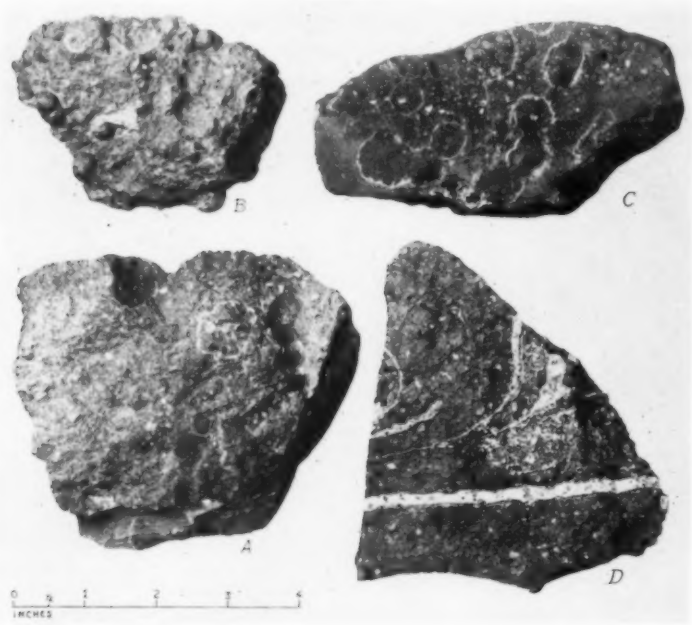

FIG. 4.—Photograph of specimens of quartz porphyry, Agate Point. These are selected from different suites which show transitional changes between globular and linear inclusions of glassy material. (*A*) Simple globules; (*B*) simple and compound globules; (*C*) smoothed surface showing compound globules with rims, in which a trace of a curving, linear, flowage structure is to be observed; (*D*) flow lines in quartz porphyry, produced by the drawing out of globules during flowage.

In addition to the sharply defined globules and the drawn-out plates which may be traced from them, there are also streaks and irregular-shaped patches of grayish-brown quartz porphyry in the bright-red quartz porphyry showing various degrees of sharpness of boundary; within a few inches a very sharp linear boundary gives

place to a minute interpenetration which lies adjacent to a merging contact. Dykelets of quartz porphyry with quartz and red feldspar phenocrysts in mottled bright- and dull-green glass are to be found cutting the red quartz porphyry; these dykelets appear to be distinct from the globule-bearing material in but a part of the outcrop; they locally merge with the surrounding rock and elsewhere form curving narrow bands parallel to the other bands in the convoluted fluxion structure.

To the north of the embayment on the west side of the peninsula, there is a particularly fine exposure of globules averaging $\frac{1}{2}$ inch in diameter of dark-brown quartz porphyry rather evenly distributed through dark-gray quartz porphyry; buff-colored rims of relatively softer material can be observed around all of the globules at the surface, and in some cases the rim attains a thickness of 2 millimeters; the alley-like globules can be readily separated from the main mass of the rock, and at certain places, where the enveloping film has been eroded, the globules can be rotated in their setting. Composite globules, which can unhesitatingly be ascribed to the arrested coalescence of individual globules, occur in all stages from two individuals just touching, through the twin-sphere stage to the well-united stage in which the annular union-furrow is barely discernible; the larger individual globules may have been formed by the coalescence of smaller individuals.

Adjacent to the globule-bearing phase of the quartz porphyry, which shows no flow lines in its glassy matrix, the rock shows a gradational change into a distorted-globule phase, thence into a beautifully banded quartz porphyry showing intricate flowage curves; the color bands decrease in thickness and tend to lose their identity as traced away from the globule phase easterly. A brecciated appearance can be observed in the phenocrysts of the finely banded material; the fine hairlike flowage lines swell around the phenocrysts on either side, though the general parallelism of these is maintained. The structure somewhat resembles the grain in bird's-eye maple. A description and figure of this phase is given by Irving.[1]

Several yards north of the previously mentioned globule occurrence, a low outcrop of obsidian with a few sparsely scattered glob-

[1] *U.S. Geological Survey, Mono.* 5, Plate 12, Figure 3.

ules of dark-grey, glassy material is traversed by a seam of brick-red quartz porphyry which contains abundant disseminated globules of reddish-brown quartz porphyry. This seam, though resembling a dyke on casual inspection, shows a merging contact with the obsidian. Small seamlets of agate cut both the black obsidian and the red porphyry, and for a fraction of an inch on either side of their walls the obsidian is bright red. The jointing in the rock passes through the globules without deviation.

No remnants of xenoliths or included fragments of wall rock foreign to the quartz porphyry were recognized in any of these outcrops.

DETAILS REGARDING THE GLOBULE-BEARING QUARTZ PORPHYRY

The lithological character of the globule-bearing quartz porphyry is not uniform for any considerable distance in the principal outcrops where it was observed. Differences are to be found in the color and texture of the glass of both the globules and the main mass; there are differences in the size, color, and proportion of the phenocrysts of quartz and feldspar which are common to both; a globule rim is in some cases prominent and in some cases inconspicuous or apparently absent. The fresh, dense, hard material is different from the equivalent material which has been exposed on the weathered surface. There are strongly marked differences between the hard porphyry and the soft material which occurs near the fluorite veinlets, though equivalent internal structures can be recognized. The color of the globules is at no place the same as that of the surrounding glass, but the degree of difference varies to an extent indicated in Table I, which refers to dense, hard material only.

TABLE I

COLOR OF GLASS IN QUARTZ PORPHYRY

Main Mass	Globule
Scarlet	dark brown
Scarlet	white
Scarlet	pale green
Grayish violet	pale reddish brown
Dark gray	dark brownish gray

The most prominently exposed phase of the fresh-looking material shows dark-brown globules in a scarlet matrix. This material (*A*

in Fig. 4) was selected for special examination and for chemical analysis.

The glass of the main mass of this rock is homogeneous, scarlet in color with a luster ranging between subvitreous and porcellanic; its hardness is 5.5, and it shows hackly and local indications of conchoidal fracture.

The globules are rather evenly distributed through this rock, from 20 to 30 appearing on a surface 1 foot square. In a specimen the globules are spherical and average $\frac{3}{4}$ inch in diameter, composite globules occur in all stages of arrested coalescence, and these have been found with a diameter as great as 4 inches. The glass of the globules is homogeneous, dark brown in color, with subvitreous luster; its hardness is 6. It breaks with a subconchoidal fracture less hackly than the glass of the main mass.

In the globule-bearing phase, generally, the density of the glass, as indicated by the quality of the vitreous luster, in both the globules and the matrix varies through a similar range; a careful study of hand specimens, however, shows that the density of the globules is occasionally greater than that of the adjacent main mass; the reverse has not been found. At a certain locality there is in the hackly fracture of the main mass a suggestion of foliation and linear parallelism which does not show in the globules. This field observation supplied a basis for inferring the somewhat earlier solidification of the globules, which, on other evidence, appear to have been liquid when the main mass was liquid.

In the selected study material, small phenocrysts of quartz and feldspar occur sporadically through all the rock, their distribution and composition bearing no relation to the globule structure, which is peculiar to the glassy part of the rock. Some phenocrysts extend across the rims of the globules. The proportions of the two minerals which occur as phenocrysts vary; in a selected specimen the volume occupied by each is approximately the same; the quartz phenocrysts are more numerous but their average size is smaller.

The quartz phenocrysts are clear and colorless, averaging 1 millimeter in diameter. Their outlines appear rounded.

The feldspar phenocrysts are commonly white, or pale grayish red; crystallographic bounding planes can be observed, though the

corners are usually rounded. In those phenocrysts which exceed 3 millimeters in diameter, zonal banding can be observed. The reflections from a freshly fractured surface are not uniformly brilliant in all the zones, and in some cases there appear to be zonal inclusions of matrix material. An example of such a phenocryst was observed half within a globule and half extending beyond.

Small amygdules occur sparingly through the main mass of the rock and also in the globules. Some of these are spherical and have diameters as great as $\frac{1}{4}$ inch, others are drawn out in irregular shapes to $\frac{1}{2}$ inch in length. Bluish-white agate is the principal amygdule filling.

Around the majority of the globules there is a film of relatively soft porcellanic material lighter in color than either the globule or the matrix. In the freshest-looking material the film is of paper thinness. On a polished surface of a hand specimen the film occasionally appears as a bleached zone lying on both sides of a curved shrinkage crack which defines the globule structure; the bleached material persists as a film around the globule even where the shrinkage crack cannot be traced, and it does not occur along other shrinkage cracks or joints which traverse the rock away from the globule boundaries. The rim material shows its maximum development on the western side of the peninsula in the black obsidian-like phase of the globule bearing material. Perfect hulls of soft buff-colored material of earthy luster up to 2 millimeters in thickness surround hard globules averaging 1 centimeter in diameter. The rock at this locality shows the effect of weathering more than at certain other localities, but the material forming the globule hull appears to be different and distinct from the brownish-gray weathering product, whose luster ranges from porcellanic to earthy.

The results of analyses by George W. Bain, of Columbia University, are given in Table II.

The composition of the selected globule material is different from that of the main mass, and, since the material is fresh looking, it is to be inferred that the composition of the globule material was different, in a similar degree, from that of the main mass at about the time of solidification.

Under the microscope, thin sections of the quartz porphyry are

found to consist chiefly of glass, devitrified glass, or both, showing perlitic structure. The outstanding differences between the glass of the globules and the main mass are that perlitic cracks are less abundant, and the ferrite (which forms cloudy inclusions related in

TABLE II

	Main Mass	Globule	Rim Material
SiO_2	71.64	76.20	74.31
Al_2O_3	13.19	11.33	4.31
Fe_2O_3	2.39	1.90	3.87*
FeO	0.18	0.28	.....
CaO	1.17	0.92	1.63
MgO	0.25	0.20	1.30
K_2O	3.85	3.42	5.46
Na_2O	2.41	2.75	7.35
H_2O+	2.28	1.81	2.26
H_2O-	2.00	0.28	0.28
TiO_2	0.31	0.34	.....
Volatile	.....	0.56	.....
	99.67	99.99	100.77

The iron was calculated as Fe_2O_3; on account of lack of material, FeO was not determined.

its distribution to the perlitic structure) is less in the former than in the latter. Microlites of feldspar are sparsely scattered through the main mass of the rock in addition to the large phenocrysts. The thin rim found around certain globules consists of pale-gray, clouded, glassy material showing perlitic structure.

INFERENCES

Bowen states that "there is only one kind of phenomenon which could be considered as definite proof of the occurrence of limited liquid miscibility. . . . . The observed phenomenon would be the occurrence in glassy, or partly glassy extrusive lava of distinct globules of material still partly glass, large or small according to their opportunity for aggregation, and of composition different from that of the main mass. Here would lie indisputable proof of the formation of immiscible liquid globules."[1] The outcrops near Agate Point show an occurrence in partly glassy extrusive lava of hundreds of distinct globules of partly glassy material of composition different

[1] N. L. Bowen, "Later Stages of Evolution of Igneous Rocks," *Journal of Geology, Supplement* to Vol. XXIII, No. 8 (1915), p. 10.

from that of the main mass. If Bowen's statement is correct, it is evident that the occurrence furnishes proof of the formation of immiscible liquid globules.

That the globules existed as such, and in a fluid state, when the main mass was also fluid is inferred from (1) the fact that both are, or were, composed mainly of glass; (2) the flowage phenomena which involve both; (3) the observational evidence that the process of coalescence of globules was taking place in the magma prior to solidification; (4) the spherical shape of the simple globules, such as is produced by surface tension between immiscible liquids; (5) the relatively uniform size and evenness of distribution of the globules in the main mass, which indirectly proves fluidity of both, since no such structure and arrangement would be expected if either had been solid when the other was fluid. (6) Further indirect evidence lies in the fact that no recognizable inclusions of foreign rock occur; the basic lavas of the wall rock would not produce xenoliths of the composition of the globules, and the globules could not represent foreign material derived in any conceivable manner from above, since the globule phase is traceable upward and laterally into banded lava showing flow structures.

The writer's interpretation of the general geological relationships in the vicinity of Agate Point, resulting from field study, is that the quartz porphyry in which the globules occur is in the latest channels of extrusion within the neck of a volcano, at very nearly the elevation where overflow took place. Basic lavas and associated pyroclastics presumably formed the walls of the extruding quartz porphyry magma for a considerable depth. The dykes of diabase on Agate Point are later intrusives which have no direct significance in connection with the phenomena observed in the quartz porphyry.

The globules in the quartz porphyry are primary structures in the glass of the igneous rock. The relatively soft globule rims are, however, regarded as a hydrothermal alteration product of the glass of the globule and the surrounding material which lay adjacent to shrinkage cracks developed around the globules. They are believed to have no direct significance in so far as the original formation of the globules is concerned, because they are not present around certain globules.

Field observations support the inference that there is a difference in the chemical composition of the globules as compared with the matrix around them. The work of Mr. Bain establishes this fact in the case of the selected samples.

The evidence that the two liquids of different composition were immiscible lies in the fact that one formed globules in the other and that these preserved their boundaries even when mechanically disturbed by flowing. The relatively uniform distribution of the multitude of equal-sized globules through the extrusion channels for an observed height of 30 feet suggests to the writer, as a more plausible theory than any tenable alternative, that a change of conditions affecting the upwelling lava caused the separation of non-consolute liquid fractions.

THE NEED OF IMPROVED TECHNIQUE IN ILLUSTRATION

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ABSTRACT

An illustration of *Astrocystites* (*Steganoblastus*) *ottawaensis* showing the results of newer methods in technique, involving gum-mountings and stereo-photomicrographs reproduced in halftone, is compared with a published drawing of the same area made under other conditions. The comparison corrects many current errors concerning the species, and the modern plate reveals new and important details hitherto unnoticed. *Astrocystites* is seen to be a true blastid and to be a nearer *Pentremites* than is either *Asteroblastus, Asterocystis, or Blastoidocrinus.*

Astrocystites was described in 1896 (9, p. 287).[1] Criticism of the generic name, because of similarity to *Asterocystis*, Haeckel, was accepted by Whiteaves and *Steganoblastus* substituted (10, p. 395)—a name suggested by Bather. Original description was republished in 1906 (11, pp. 316–17) and additional matter given. A more complete study of the cotypes was made by Bather (3 [1914], pp. 193–203) and illustrated by six text figures and one plate. Bassler, in 1915 (1, p. 83), re-established the name *Astrocystites*.

Bather has many times referred to difficulties presented by the cotypes of *A. ottawaensis*. In 1900 (2, p. 210) he stated, "BB (5?, sutures not clear)."[2] Again in 1914 (3, p. 195):

> Except for the tegminals and cover-plates, all the thecal elements are closely united, so that *it is difficult to distinguish the sutures*. This difficulty is enhanced by the pitted ornament of the surface and by the very deep folding of the plates which form the adapical system.

And again (3, p. 196): "The rhomboidal area above the shoulders of the radials and between the grooves is filled with interambulacral plates—*their outlines are hard to see* (Text-fig. 3)." This figure is here reproduced from a photographic enlargement and becomes our Figure 1.

[1] The introductory number—in this case "9"—in the parenthetical references refers to the corresponding number in the bibliography at the close of the article.

[2] The italics in this and in following quotations are the author's.

Through the kindness of Dr. E. M. Kindle and the Geological Survey of Canada we have been allowed a long period for study of cotypes A and B. More than fifty differing areas of these specimens were prepared by using gum-dammar mountings under cover-glass (8, pp. 101–4, Plate III) and each area was then photographed two or more times—using a difference in angle of view of some 15° and an enlargement of ten diameters. Pairs of these photomicrographs were mounted as stereograms (6) to secure relief. Four of these, reproduced by purely mechanical processes and without retouching of either original negatives or prints therefrom, are here used as plates.

To make our enlargement of Bather's figure commensurate with Plate I we chose, as the two most definite and yet distant points of the drawing, the upper end of the common radial suture and a point where a line bisecting deltoid vertically would first encounter its orad suture. In Bather's figure we take the stippling to represent thecal grooves and hollows, and the lines, by their boldness, faintness, or broken character, to represent either relative boldness in appearance of sutures or degree of certainty as to presence and direction.

In making comparisons between Figure 1 and Plate I we shall endeavor to show: first, that newer methods may enable anyone to see clearly details which under ordinary examination could not be correctly drawn; second, that newer methods are capable of making manifest many details heretofore wholly unseen; and third, that older methods have led to misinterpretation of detail and to crediting the species, through drawings or written description, of structures which it does not possess.

We wish particularly to emphasize that the conflicts in interpretation to be pointed out are wholly due to difference in methods employed and not to any difference either in diligence of search or keenness of vision.

In Figure 1 a straight line connects the pair of dark, roundish, and nearly centralized spots, which we will for the present call the right and left "pits." In Plate I this line is seen to be formed by two distinct sutures which meet midway between these pits and there form an obtuse angle of about 165°.

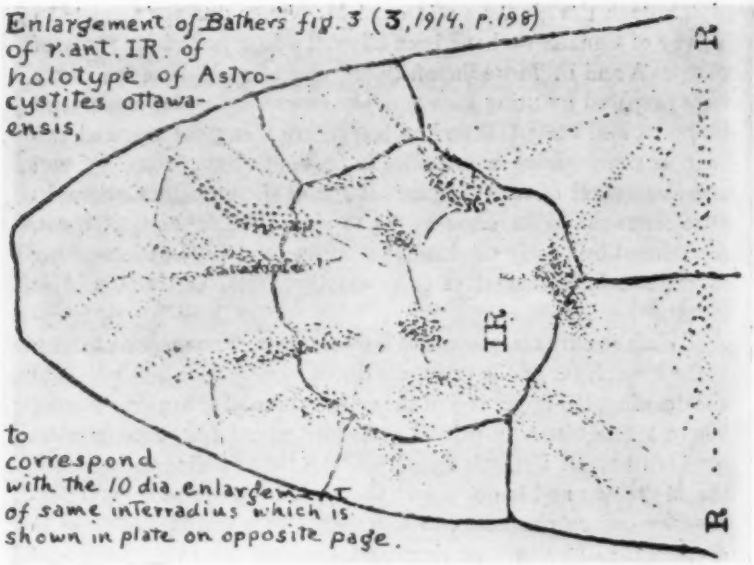
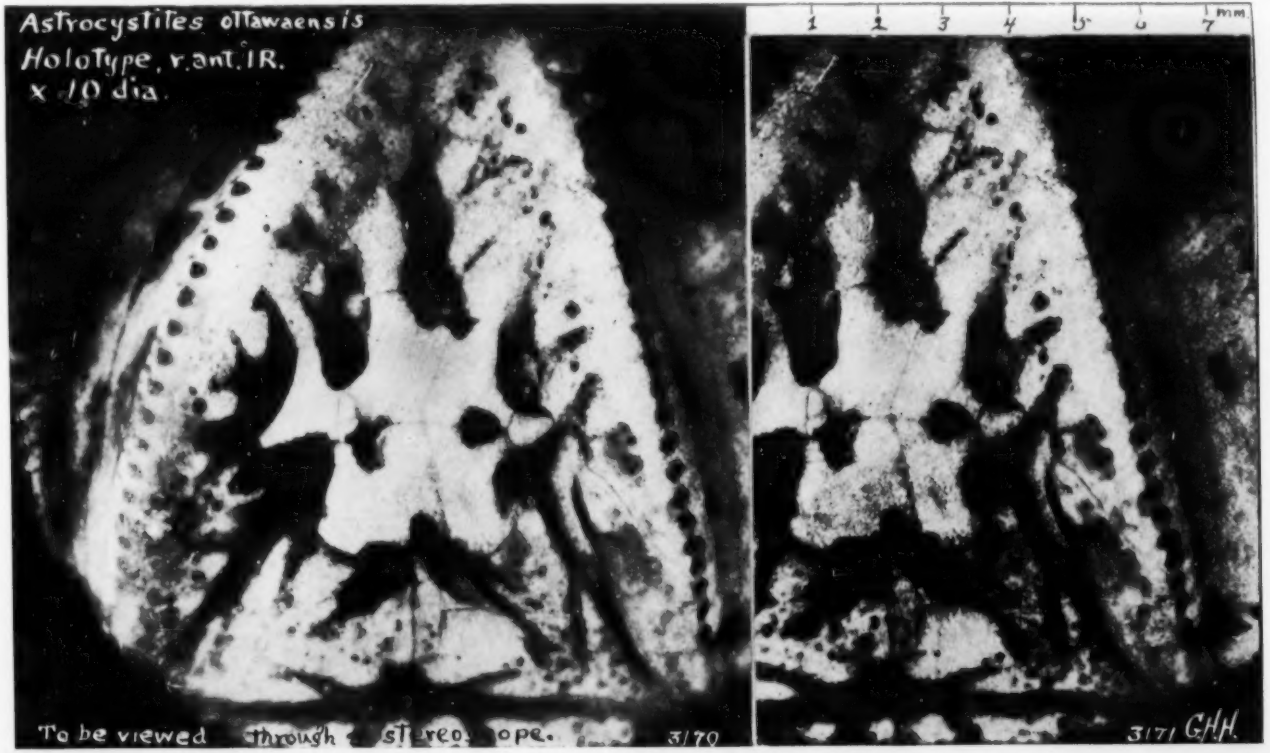


FIG. 1

From this angle (Plate I) a very distinct, straight suture is seen to run south of southeast (as in map-reading) and to enter the right-hand wing of the bifurcated and branching cavity which rests just over and upon the shoulders of the two radials. Measured on the plate, this suture is continuously visible for a length of 19 millimeters. Not the slightest trace of any portion of it seems to have been seen by the author of Figure 1.

A little to the left of the upper end of the last suture, another, running north-northeasterly, may be very clearly traced (Plate I) for a distance of 14 millimeters or to a point about 3 millimeters from its upper end—which lies buried in the lower, right-hand sinus of the large, upper median hollow. This hollow is represented in Figure 1 as if it were double, and from the lower end of the right-hand member two lines are drawn. The left line is broken, indicating some doubt as to its verity, and it is not continued to meet the suture connecting the pits, yet this line probably represents the very


Astrocystites ottawaensis
Holotype, r. ant. IR.
x 10 dia.
To be viewed through a stereoscope. 3/70
1 2 3 4 5 6 7 mm
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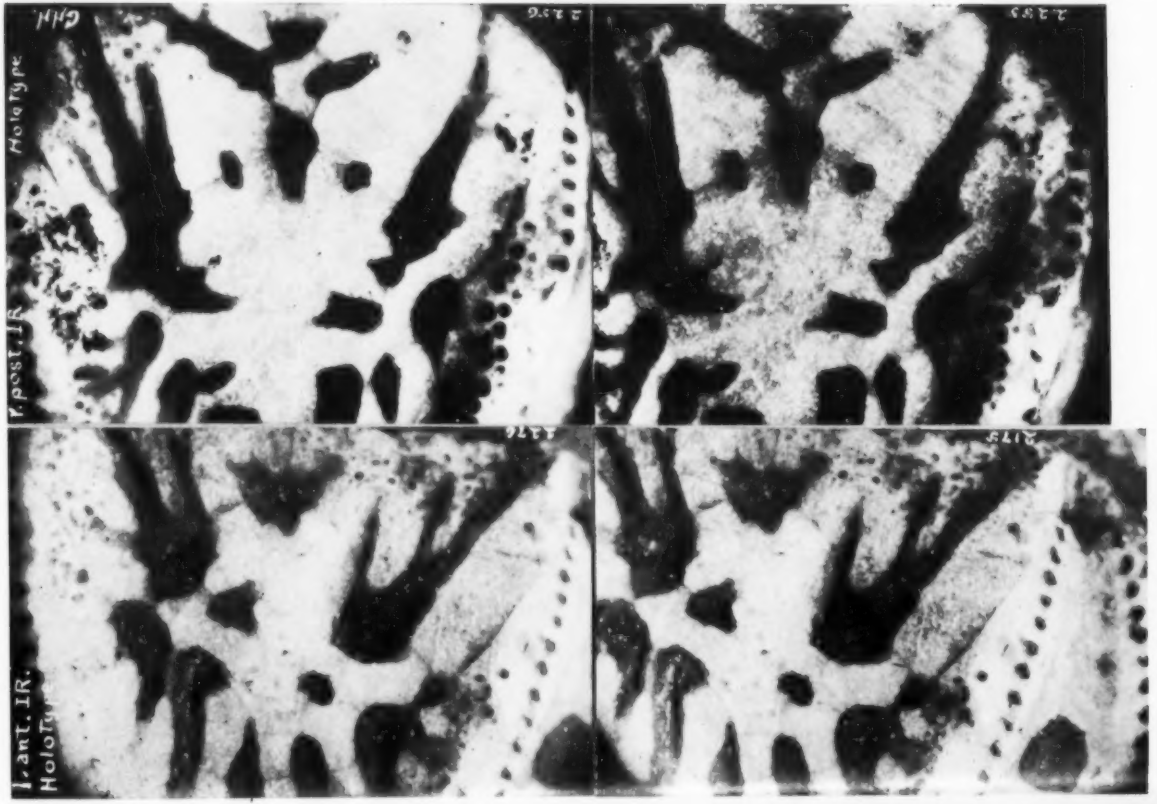
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similarly placed suture in Plate I. The more clearly drawn line to the right (Fig. 1), which is made to connect the same upper hollow with the right pit, has not the faintest trace of evidence in Plate I. From the right pit (Fig. 1) a short, broken line is seen to run northeasterly. This line, also, is not a suture but, through a stereoscope, it will be seen that there are parallel planes of fracture of calcite near this position.

A fifth line, and the boldest within the interradial area of Figure 1, connects the southwestern edge of the right pit with the hollow lying southeast of it. This line is markedly curved but Plate I shows no trace of any portion of it.

A sixth line of Figure 1 runs a short distance west-southwesterly from the left pit. There is a true suture shown in Plate I in practically the same position.

A seventh and last line within this interambulacral group (Fig. 1) is the broken line running northwesterly from the left pit and connecting with the crescentic hollow lying in that direction. This line is slightly curved and is about 13 millimeters long. No suture is to be detected here in Plate I, but there is a line 6 millimeters long that represents a suture running north-northwesterly from left pit and entering the hollow to the right of the crescentic hollow last mentioned.

Two short sutures in Plate I enter the upper left portion of the left pit and cut off a small interradial plate. The suture which enters the left side of the right pit appears again to the east of it as a line 1 millimeter long, and at the end of this line two short sutures, one running north-northeasterly and the other south-southeasterly, cut off a small interradial plate on the east of the group. Neither of these sutures appears in Figure 1.

Of the seven lines just noted in the figure which Bather used, there were three which were wholly in error and four which were partially so. No future student, with this figure as guide, could ever make a reasonable analysis from the hesitation and confusion there presented. On the other hand, the merest tyro could, from Plate I, easily and correctly reproduce the eight true sutures there so clearly shown.

Whoever will take the pains to use a stereoscope with these

plates will be enabled to see many lines caused by cleavage of calcite, many places where plate surfaces have been split off along cleavage planes and left definite walls on one sutural boundary, marks left by tools used in cleaning, and surface loss from other causes. Sutural lines, being superimposed in vision, are to be seen more distinctly; apparent curves are often seen to be but deeper portions of a uniform suture whose plane is not perpendicular to surface, and lines of fine black spots appear to be but remnants of a diffuse muscular system. To so view the stereogram one only needs to remove the view carrier, place the line dividing the views directly over the middle of the track, and then, by slightly raising or depressing a plate corner, cause the two views to combine in vision. The advantages noted aid in determination of sutural detail.

It should be borne in mind that this comparison is not an attempt to show that photographs may contain a greater wealth of detail than drawings. One value of a drawing lies in its ability to present only one kind of detail and to omit all extraneous matter. We are discussing a matter of sutural detail. One purpose of Figure 1 seems to have been to present this so far as it could be detected. Its trustworthiness or value, in this particular, is to be determined only by the completeness and accuracy of the kind of detail it intended to show. If any method of viewing the object, either directly or through the medium of some mechanical representation, would show desired details more clearly or with greater fulness, that method should be used to obtain data for the drawing. It is this superiority only which we claim for our plates. If other detail shown may be made to help in interpretation or verification, so much the better.

The case against Figure 1 becomes more serious when we pass to the consideration of other sutures there shown. Those bounding the interambulacral group are nearly correct, as is also the suture separating the radials. There are, however, three sutures drawn as running inward from each side of the figure, and these six sutures are wholly in error.

In the position of the right-hand member of the uppermost pair, there is shown, in Plate I, a line of fracture along a cleavage plane of the calcite, and a bit of the exterior of the plate is lost below it. This condition is clearly seen when a stereoscope is used, and other

parallel fractures may be noted below it. Thus is one member of this uppermost pair of false sutures accounted for. The other or left member is apparently due to a conception that there should be a mate for the one already drawn. Not the least trace of such a mate can be found in Plate I.

The pair of sutures next below these are made to run in from the boundary of Figure 1 and connect with the upper part of the circlet of sutures surrounding the interradial group. The right-hand member of this pair runs west-southwesterly and enters the upper portion of the crescentic hollow. In Plate I (using the stereoscope) there may be seen a loss of stereom here which was probably due to a tool mark, but no trace of a true suture. The line entering the west "crescent" runs east-southeasterly. In Plate I we may see two tonguelike grooves which between them carry out an extension of the left side of the crescent. Plate grooves which connect with the hollows—and these are very numerous over the theca—lie usually over the plate surfaces and by themselves cannot be taken as evidence for sutures. The clean and uninjured edge of the deltoid outside of this crescent shows nowhere the slightest trace of a suture. Not only are there no such sutures as the four last noted, but these were omitted altogether in a figure used by Bather (2, p. 210, Fig. VII, 1 and 2; and 3, p. 195, Fig. 1), which illustrates two other interradii of the species. On this evidence we may consider them as nonexistent.

Next below the last false sutures of Figure 1 we find still another pair which are indicated by lines expressive of the greatest assurance. For these lines, again, there is not the faintest shadow of evidence either in Plate I or in eighteen other areas where they might be expected in cotypes A and B, for careful search under gum-mountings has been made for them. We are compelled to conclude that the only reason for drawing them was the theoretical one that the radials must have upper limits. Bather himself has said (3 [1914], p. 196):

> From the top of the interradial sutures, the shoulders of the radial slope upwards toward the subvective groove, and the sutures bounding them can be traced for some distance. The point at which they meet the flooring-plates of the groove *cannot, however, be distinguished,* owing to the close union of the various plates in the neighborhood of the groove.

If now Plate I should show true radio-deltoid sutures running in a direction widely at variance with those drawn for Figure 1, it would not only strengthen the claim that the newer methods may reveal sutures heretofore wholly unseen, but it would at the same time relegate to limbo those shown in Figure 1.

Before pointing out the true radio-deltoid sutures we may treat briefly of the outer boundaries of Bather's figure. The lower boundary is very properly left in an indefinite manner. The upper boundary represents a true suture separating the deltoid from the orotegmenal. Were the lateral boundaries also intended for sutures? If they were meant to represent the line of brachiole pores which form lateral boundaries of the deltoid, they should have shown traces of the presence of these pores and have omitted the purely gratuitous indentations at supposed upper limits of radials. If now one will measure the distance between the pore lines, crossing the deltoid just below and again just above the interradial group, he will find that in both instances the width in Figure 1 is very markedly less than that obtained in Plate I. It would seem that a fair conclusion would be that the lateral lines of Figure 1, though indicated after the manner of its principal sutures, were not intended to represent the brachiole-pore lines. If not, however, they represent nothing shown in Plate I and should have been omitted.

Turning now to the radio-deltoid sutures, we will begin tracing these at a point 14 millimeters inward from the right-hand margin of Plate I and 24 millimeters above its base. This is at the left side of the third complete brachiole-pore, counting upward. From this point we may trace for a distance of 25 millimeters a fine, slightly sinuous line of a suture running northwesterly. Through a stereoscope it may be easily followed for another 8 millimeters or to the point where the easternmost small plate of the interradial group touches the deltoid. This line represents the outer edge of the sutural plane separating the radial from the deltoid. The interradial end of this suture lies at the point where the author of Figure 1 placed an orad angle of the radial at the right, and from which he drew his conjectural sutural line running east-northeasterly. The difference in angle between the real and the formerly suggested position of this suture is about 65°.

Through a stereoscope we may note that the hollow and groove nearest this suture has been partly cleaned out and that the white portion, a bent band some 4 millimeters wide and 20 millimeters long, is as deep or deeper than the black matrix which still borders it. We may also see that this groove deepens as it approaches the plate border. Relieved of the necessity of judging which is matrix and which shadow (an exceedingly important item) and seeing the structures here as if in true relief, we may note at once that the plane of the radio-deltoid suture is not vertical to the plate surface and may look for indications that the deltoid wing laps over the radial and that the face of the sutural plane is waved. The radial face of the suture appears to have three transverse crests and two troughs. The uppermost crest is seen to pass over the upper end of the cleaned stereom of the deep groove. A more gentle crest occurs about 8 millimeters (measured on plate) south-southeasterly of this, and the third crest occurs just before the suture reaches the line of brachiole pores, or some 20 millimeters below the second crest. These crests and troughs are very significant adaptations for ray extension.

The left side of Plate I is made to include more than can be viewed in relief, but another radio-deltoid suture, showing the long and shallow trough, may there be seen. Because the area over which it runs has been but little cleaned, and still shows spine pits of plate surface, the suture is not so easily followed as was the last.

As these true radio-deltoid sutures were not drawn in Bather's figure, it will be proper to call attention to their presence in four other positions in the holotype. This suture with its crests and troughs is very clearly shown in Plate II on the left side of the upper figure both by the very distinct line of its outer edge and the difference in shade between the white weathered calcite of the deltoid wing and the darker calcite due to the splitting off of a portion of the radial. With a stereoscope we may also see that this cleavage from the edge of the radial lip did not pass the suture but left a distinct clifflike boundary on the edge of the deltoid. Similar conditions also reveal a radio-deltoid suture on the left side of the lower figure of the plate. Its right side is extended beyond the field of

stereoscopic vision but there also portions of radio-deltoid sutures may be easily noted.

We have shown these sutures in six different areas of the holotype. Gum-mounting has revealed their presence in all ten areas in each of the cotypes studied. The uppermost crest is usually more or less buried in matrix-filled hollows, but the long, shallow trough lying orad of the lowest crest is readily found—though becoming a nearly straight line in some positions and particularly so in *Post. IR.*

Bather (3, p. 195, Fig. 1; and 2, p. 210, Fig. 2) has himself presented evidence against those portions of the orad radial boundaries which were incorrectly drawn in Figure 1. He evidently saw a portion of the true radio-deltoid suture on the left side of the post. *IR* in cotype B and for this one position used a more nearly correct line. After passing the upper right-hand angle of the radial, however, he felt constrained to follow a branch groove of the crescentic hollow to reach the outer edge of the ambulacrum. The aborad extension of the suture there detected was carried out for only about half the length made visible by gum-dammar mountings. The fact that the growing deltoid tips rested on a long, supporting floor of a radial sinus is an item of exceptional interest both from a morphologic and taxonomic aspect. In *Pentremites* we find a similar provision for transfer of floor-plates from the radial to the deltoid, but there the deltoid wing forms the under portion of a beveled suture.

The true character of the deltoid is clearly revealed in Plate IV. Crushing in of *l. ant. IR* of cotype B drove contiguous edges of two radials deeply into the body cavity, and the radial at the right was also thrust northwesterly. This movement displaced the cluster of interambulacral plates as a whole—the lower right-hand edge of the group was turned deeply inward and the opposite edge thrust slightly outward. The deltoid resisted this twist to a marked extent. Its left side was broken and the portion of the deltoid aborad of break may be seen, through a stereoscope, to be thrust outward. The displacement did not pass the deep and weak median groove, though the fracture did so. The inward movement of the right radial carried with it only the very thin, narrow, and youngest portion of the deltoid wing. The fracture and the broken tip are the only visible yieldings to tortional stress. There were no displacements, of even

a slight nature, that would suggest that the deltoid was a composite plate. The separation between the deltoid and the plates on its aborad edge was along the weak, sutural boundary of interradial circlet and then along the radio-deltoid suture whose characteristic curves are well displayed for more than half their length. The balance of this suture (below fracture) is seen to reach the border of brachiole pores and leave no room for adambulacrals. The deltoid here proclaims its unity in a manner which every unbiased student must recognize.

It is possible that the lateral boundary lines of Bather's figure were meant to indicate the probable position of the inner boundary of an inferred series of adambulacral plates. He evidently believed that *Astrocystites* possessed such, for he states (3 [1914], p. 199): "It is clear that the floor-plates and adambulacrals are independent morphological elements." Before this, however, he had said of these supposed adambulacrals (3 [1914], p. 196): "Whether they are really distinct from the floor-plates of the grooves is *uncertain*." The radio-deltoid sutures shown in our plates all reach brachiole-pores, and in not a single photomicrograph which we have made is there the slightest trace of, or evidence for, any adambulacrals bordering the food-groove, or for any sutures whatever running in from the line of brachiole pores toward the interradial cluster, save alone the radio-deltoid suture now made visible by newer methods.

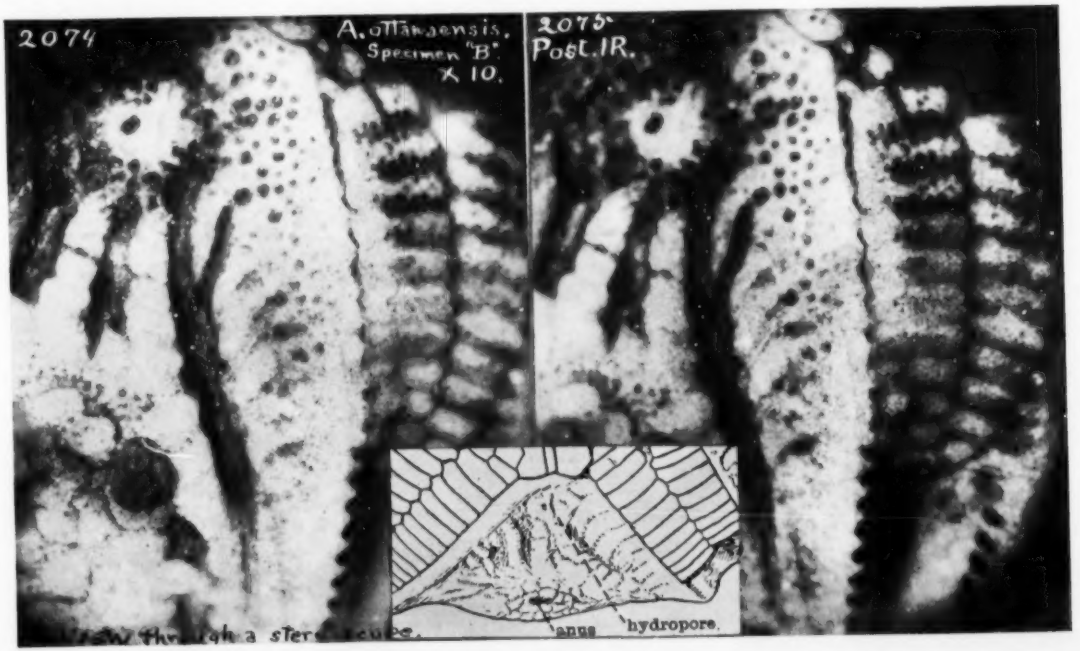
In this connection we may consult Bather's Figure 5 (3 [1914], p. 200). Of this figure we have enlarged a portion to represent 5 diameters and have used it as an inset for Plate III. In his figure he left all immediate borders of food-grooves without any indication of structure save alone on the right-hand side of *Post. IR*, where in dotted lines, denoting uncertainty, he presented nine curved lines running from grooves on the deltoid and nearly or actually reaching a row of ten cover-plates. These lines might be interpreted as evidence for sutures between a series of adambulacrals, though one would expect to see a line running to next to the last cover-plate. An examination of Plate III will show that these lines do not exist, though three parallel cleavage planes may be detected. The border of this ray should have been drawn as were the other nine borders, and these dotted lines are but "the substance of things hoped for,

the evidence of things not seen." The groovings of the deltoid, of course, require interpretation, but we have already pointed out that they cannot be taken as evidences for sutures, for in most cases the plategroovings, which Bather called "folds," run at right angles to sutures.

In *Blastoidocrinus* the sides of the deltoids were regularly grooved (see 4, Plate V, fig. *j*) and each ridge supported the external basal ossicle of a brachiole. These grooves do not indicate sutures but they do show that plate-widening was constantly affected, externally, by contact with brachiole bases. The aborad margins of *Blastoidocrinus* deltoids were also grooved, but the cause here was plate extension along a border of spiracles (5, Plate III, Figs. 1 and 2). In *Astrocystites* the plate-groovings along aborad borders of deltoids are due to the same cause. The forking, often producing dendritic figures, is due to the coalescence of spiracles during development—the beginnings of such union were noted for *Blastoidocrinus* (5, p. 210). *Astrocystites* reduced, during ontogeny, some fifty or more spiracles in each deltoid to a final five. The last pair of enlarged spiracles approach the condition presented by *Orophocrinus*. Were the deltoid wing so shortened as to leave each member of this pair in conjunction with an ambulacrum we would have a still closer approach. In a future paper we shall deal with the structure of the ambulacrum in *Astrocystites* and present additional evidence for spiracles of the Blastoid type.

The photographs for Plates III and IV also show some interesting details indicating the possession of brachioles which rested over both the deltoid border and the lateral ends of cover-plates, or along those peculiar belts which are destitute of spine pits. The cover-plates were locked along their medial ends, and their lateral ends rested on a significantly beveled suture on the deltoid edge. In Plates II and III lunate openings may be seen between the deltoid and the cover-plates. In several places there is evidence for small proximal brachiolar ossicles which were inserted between lateral ends of cover-plates but which did not penetrate to a position between floor-plates (see outer side plates of *Pentremites*). These and still other details of food-grooves cannot be treated here.

Lateral borders of deltoids in *Pentremites* reach the line of brachi-


2074
A. ottawaensis.
Specimen "B".
× 10.
2075.
Post. IR.
hydropore.

3

ole-pores, and the inner surfaces of the plates have saggitate outline. Deltoids of *Blastoidocrinus* are similarly bounded but their aborad angles kept pace with ray extension and the deltoid of an old specimen became very markedly saggitate (4, Plate V, *n–o*). In *Astrocystites* we have a true deltoid of still more saggitate form, this being in part due to orad position and circular grouping of the cluster of small interambulacrals which in *Blastoidocrinus* had a laterally extended grouping and a more aborad position (4, p. 99, Fig. 1).

Plate I has still much interesting detail to reveal but we will confine ourselves here to the interradial cluster. Its boundary, measured on the plate, is close to 144 millimeters long. Of this some 38 millimeters of the suture is visible, but the buried suture cannot be drawn without using inward bends over hollows, or as Bather had it drawn for his figure. Four points of particular interest in this circlet may be noted:

1. The inward bends across basins may be taken as evidence that the group of interradials had margins beveled so as to overlap both the deltoid and the radials. This beveling, using stereoscope, may be detected in several places. It is perhaps best seen in the right side of the hollow lying between the left-spiracle-crescent and the upper median hollow. Next the radials the beveling is not so pronounced, yet nowhere is any portion of these boundary sutures perpendicular to the plate surface. Adaptation is here evident. The deltoid seems to have required freedom from the pressure of the interradial group. The latter acted more as a protecting cover than as a deltoid support.

2. The interradial group of Plate I may be seen (with the stereoscope) to have suffered an uplift of its southwesterly edge in which all plates were moved as a unit, save alone the very small seventh lying over the common radial suture. This uplift was greater than now appears, for though the present surfaces of lower interradials are still raised above the radial surface, yet the former will be seen to have lost considerable surface through the splitting off of stereom. The tipping of this cluster is evidence again for a loose, sutural boundary such as was noted in Plate IV.

3. In Plate I we may notice that the interradial group suffered a slight, clockwise, rotational movement which affected its plates as

a whole—save alone the seventh. On the upper ridges this displacement equals about 2°, but where the group was elevated the rotational displacement appears to exceed this.

4. Bather has written (3 [1914], p. 197):

> The folds between the ridges are very deep, especially in the interambulacral area, notably a fold just below the adoral interambulacral (Text-fig. 3). . . . . It may be inferred that the sole effect is to endue the theca with quite exceptional rigidity.

The inner surface of the thecal plates is even, not ridged, and therefore the deeper the groove the weaker the plate. Here is a reason why the left fracture seen in Plate IV did not pass the median line. The circlet of sutures in all interradii is very materially weakened, not only by the thinness of the deeper portions of the basins, but also by the size of the openings which reached the interior. Along the interradio-deltoid suture shown in Plate I we find some 58 millimeters still buried in the matrix of spiracle-hollows, and along this weakened portion of the suture we have evidence which will allow us to postulate some 25 millimeters or more where openings existed and along which the deltoid had no contact whatever with interradials. For the present we may accept the beveling, the tipping, and the rotational displacement of interradial groups as evidence that the surrounding sutures were not so formed as to give "quite exceptional rigidity," but, on the contrary, to give quite exceptional freedom. These conditions are such as we might expect of groups of plates in part adapted to adjust themselves to the volume of spiracle outflow.

Of these interradial groups Bather has written (3 [1914], p. 196):

> To judge from the folds, three or four small plates have joined in the center of each area, except the posterior, to form a *relatively large plate* of somewhat swollen appearance (*IR*). *This plate* rests on the radials and other smaller plates lie between it and the grooves.

The clearly drawn boundary of the interradial group in his figure leaves no doubt as to the outer limitations for his "Single" (*IR*) plate. He considered this group to consist of one plate because he believed, "The tendency of the species is to fuse the originally indefinite smaller plates into a few larger plates of definite arrange-

ment" (3, [1914], p. 195). This "plate" or cluster does "rest on the radials" but there are no "other smaller plates" which "lie between it and the grooves." We find in Plate I four larger central plates and three smaller ones inside its boundary—and there is possibly an additional small plate within the base of the median spiracle-groove at the point of its lower bifurcation. We have, then, not "three or four" fused plates making up this group but seven or eight distinct and unfused plates.

The "somewhat swollen appearance" of these *IR* groups we may explain by assuming a primitive four which during their lateral extensions were also subject to progressive thickening, and that the three or four smaller plates are younger and thinner. In 1907 (4, p. 99, Fig. 1) we gave an analysis of *Blastoidocrinus* which showed the details of five interbrachial groups. Next the base of each deltoid was a somewhat linear series of plates numbering from ten to twelve. Extension of the theca, and the separation of the deltoid and the radial by means of bibrachials, seems to have required the occasional addition of small terminal plates to this transverse series (4, p. 118). We suggest that, in *Astrocystites*, increase in size, extension of deltoid wings, aborad movement of radials, and some need for adjustment to spiracle flow were factors conducive to the formation of additional ossicles. In many cases these small peripheral plates will be found to have their longer and deeper sutures next more central plates and their shorter and shallower sutures next the outer boundary. This may be seen in Plate I where the left-hand plate of the cluster has an outer curve bordering a comparatively large oval pore but is itself supported by two larger and thicker central plates with only a small pore between them. The plate at the extreme right of the cluster has an unbroken contact with two thicker, inner plates and a shorter and less deep suture next the deltoid. The close union and exceptional solidity of the more central plates of the groups; the extreme weakness of the group boundary; its beveled sutures; the evidences for slight movement as a whole; and the association of the small, narrow surfaced, and more or less separated marginal plates with the larger pores on the group margins—all indicate that the structure was long associated with some important

function. We believe that for the orad half of the circlet this function was the discharge of brachiolar waters along the aborad margin of the deltoid.

The line of evolution in *Astrocystites* has been distinctly away from the *Blastoidocrinus* type in this particular, and approach to the *Pentremites* type is marked. In *Blastoidocrinus* the flow of spiracle waters was of the *kataspire* type, (7, p. 165) though in maturity the flow from the newer brachioles became more nearly lateral in direction. During the ontogeny of *Astrocystites* the flow was at first of the *kataspire* type, but in early youth the newer brachiole pores discharged their water laterally, and in maturity the newest pores discharged through *anaspires*—the direction of flow in *Pentremites*.

Plate I has yet much to tell concerning surface groovings, pores, and ambulacral areas. We hope we have presented evidence which demonstrates the presence of large and interesting deltoids and the absence of adambulacrals. The complete proof for other statements and the presentation of new matter will require additional plates and will be given in a future paper.

It may seem to some that in these comparisons we have accused the author of Figure 1 with imagining those things which he could not have seen and of leaving unnoticed those things which he ought to have seen. Let us reassert, therefore, that the differences in the representations of the areas reviewed are entirely due to differences in method. Whenever gum-mountings under cover-glass are used, an immense amount of light-scattering is prevented and some penetration secured (8, pp. 101–4). The calcite of the test reflects more light, and all carbonaceous matter less light. Herein lies the reason for the differences which may be noted between the form of the stippled areas of Figure 1 and the darkened areas of Plate I. The boundaries of the filled grooves and hollows are very indistinct when the rather uniformly colored exterior of the specimen is viewed without gum-mounting. The methods used for Plate I brought these indistinct differences into violent contrast. The question is not one of mental acumen but one of method.

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REVIEWS

Introduction to Physical Geology. By WILLIAM J. MILLER. New York: D. Van Nostrand Co., 1924. Pp. 435, figs. 351.

This book has been prepared as a companion volume to the author's *Introduction to Historical Geology* with which it is intended to serve as a text for a one-year college course in general geology.

It is difficult to write a text that will satisfy other teachers in all respects; hence this text to the reviewer has its strong and weak points. On the whole this volume hardly seems to be on a par with its predecessor. Minerals, rocks, and structure are discussed in the first chapters, which is the logical place to treat the materials upon which geologic processes act and which exert a strong influence upon the resultant features. It does not seem advisable, however, to present here the technical aspects of structure, especially in an elementary text. The series of chapters on gradational processes is interrupted twice by a chapter on volcanoes and one on relief features. This seems to be neither logical physiography nor sound pedagogy. Genetic relations could be better presented to the student with some rearrangement of the chapters. The final chapter on "Economic Geology" will give the elementary student an appreciation of the economic importance of the science, a phase which often receives too little attention in a "general" course.

In places the style and subject matter seem rather elementary for a standard college course. The placing of common words in parentheses, as "removal . . . . by a natural process (erosion)," is a conspicuous fault. Although the book is not written for students of chemistry, the usage of soda for sodium, etc., is not permissible in a textbook of science. A few terms, e.g., "fossil," are not defined where first used. The reviewer prefers to have his students form gradually their ideas of geologic time rather than to have the expression "millions of years" constantly before them early in the course.

The illustrations are mainly from photographs by the author. On the whole they are clear and to the point, although some could well be replaced by others to bring the topic more clearly before the student. The style of the legends is somewhat inconsistent, and in a few instances the legend is incorrect.

Most of the faults that have been noted can be removed by a careful revision. After such revision the book should be an excellent one for the general reader and should make a good text for a brief college course.

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